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SEARCH FOR MAGNETIC MONOPOLES*

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ABSTRACT

If magnetic monopoles exist, they are evidently too massive to have been produced in man-made radiation, too rare to have been observed directly in cosmic radiation, and too energetic to have accumulated in ferromagnetic surface minerals. Primordial monopoles which escaped immediate recombination are destined to undergo progressive acceleration by the solenoidal magnetic fields they encounter in the universe. They would by now have acquired energies of the order of 10^{20} eV and should therefore arrive isotropically, unaffected by the earth's atmosphere or magnetic field. Secondary monopoles produced in the upper atmosphere are also likely to have more residual energy than they can lose to the atmosphere. Ocean water of more than the penetration depth would thermalize monopoles without immobilizing them, and thus allow monopoles to accumulate in the magnetic component of deep sea sediment. The slow deposition rate of sediment thus makes it the most promising terrestrial source of monopoles.

We have constructed apparatus capable of extracting magnetic monopoles from massive quantities of sediment, accelerating them to 50 GeV and detecting them by an array of scintillation counters. Assuming that monopoles are bound only to ferromagnetic and paramagnetic materials, we have established an upper limit arrival rate of one per cm^2 in 8×10^{16} sec for an energy $\leq 4 \times 10^{15}$ eV monopoles and one per cm^2 in 6×10^{17} sec for an energy $\leq 2 \times 10^{14}$ eV monopoles, of either polarity, of charge larger than one sixth Dirac value, and of mass up to 14,000 proton masses, with a confidence level of 95%. For comparison, the arrival rate of particles generating extensive air showers accounting for more than 10^{18} eV is one per cm^2 in 1.5×10^{16} sec.

I. RATIONALE OF THE SEARCH

Accelerator experiments [1, 2, 3, 4] have provided evidence against the existence of free monopoles less massive than 5.0 GeV, the heaviest which could have been produced in the 70 GeV Serpukhov synchrotron. Two experiments searching directly for monopoles incident with the cosmic radiation or produced by energetic primaries in the upper atmosphere have established an upper limit for the arrival rate of one north monopole per cm^2 in 10^6 years (total flux or area-time product searched of 3×10^{13} cm^2-sec)[5,6]. However, these experiments depended on collecting monopoles following the earth's magnetic field, namely north monopoles of sufficiently low energy to have been thermalized by the atmosphere; this implies a maximum arrival energy of $\sim 8 \times 10^{12}$ eV; a primary monopole of Dirac[7] charge, 68.5 e, falling from infinity into the earth's magnetic field would acquire an energy of 3.8×10^{12} eV, and a monopole with Schwinger[8] charge twice as much.

A third experiment[9] searched for monopoles which might have accumulated during geological periods of time within one centimeter of the surface of magnetic mineral outcrops. This experiment does not depend on magnetic funneling and would therefore have detected north monopoles of slightly higher energy, limited only by the condition that they were stopped within one centimeter of rock. It established an upper limit of one north monopole in 10^{13} cm^2-sec.

Two factors of possible relevance to these and subsequent conclusions should be mentioned. Energy-range relations for monopoles are customarily based on the assumption that they lose energy only by ionizing like a relativistic particle of electric charge 68.5 e, an assumption justified primarily by lack of information, but energy loss mechanisms other than ionization may exist. A second factor, discussed by Ruderman and Zwanziger,[10] is that monopoles of of opposite charges have a very high binding energy, and lose energy rapidly within the interaction region where they were produced. This implies that we can hope to detect only primordial monopoles which have been created in an environment of more abundant energy than the earth's sphere, or that all searching should in fact extend to much higher energies than the kinematic threshold for monopole production by nucleon-nucleon collisions.

If monopoles exist they could have been created in the primordial fireball along with the more common elementary particles. The few monopoles which escaped recombination in the primordial fireball are destined to acquire ever-increasing energy as they traverse the universe. The magnetic fields they encounter are predominantly solenoidal, making the cross section for acceleration substantially greater than the cross section for deceleration. Taking into account "known" galactic and intergalactic fields, Goto[11] and Alvarez[12] conclude that at the present age of the universe, primordial monopoles should have acquired an energy between 5×10^{19} and 5×10^{21} eV (for Dirac charge). Subsequent discovery of the 2.7° K background radiation which pervades the universe suggests the existence of an energy loss mechanism that would limit the upper part of the monopole energy spectrum, namely monopole-photon collisions. Also, the monopole-photon collision could be the mechanism for generating high energy photons, or conversely, the high energy photon flux limit can be used (somewhat indirectly) to establish upper limits on monopole fluxes.[13] At any rate, it is obvious that monopoles arriving from interplanetary space would have such an energy as to evade detection by any of the experiments cited above. Unaffected by the earth's magnetic field or the earth's atmosphere, they arrive isotropically and penetrate through the earth, some of the less energetic ones stopping at widely distributed penetration depths. The only terrestrial material in which monopoles may be expected to have accumulated preferentially is deep sea sediment. A monopole of appropriate polarity thermalized by the ocean water will drift to the bottom along the direction of the earth's magnetic field and become trapped near the surface of the sediment. A given amount of sediment represents a substantial area-time flux in view of the very low sedimentation rate in deep parts of the ocean (typically 0.1 mm/century in the Pacific and up to 1 mm/century in the Atlantic).[14]

Since attention was called to this circumstance by Goto, Kolm, and Ford,[9] three experiments were performed to search for monopoles in sediment. Alvarez et al[15] rotated samples of sediment through coils which would have detected the magnetic current corresponding to one half of a Dirac charge[16]. Vant-Hull[17] passed sediment through a superconducting ring in which a single quantum of magnetic charge would have induced a measurable change in quantized current. Fleischer, et al[18, 19] used a pulsed magnet to extract monopoles from manganese nodules and identify them by physical tracks in Lexan polycarbonate resin. The last two experiments achieved the high flux limit by virtue of the enormous age of manganese nodules; it amounts to an area-time product of 4.9×10^{17} cm^2-sec. An even higher limit has been set by Alvarez et al[20] in a recent search in lunar samples. For comparison, the energetic primary particles which give rise to extensive air showers accounting for more than 10^{18} eV energy arrive at the rate of one per cm^2 in 10^9 years ($\sim 1.5 \times 10^{16}$ sec).

It has been the aim of the present work to develop experimental apparatus capable of searching sufficient quantities of material to achieve comparable upper limits on the arrival of monopoles, or that is, to detect monopoles if they arrive about as frequently as very high (10^{20} or so eV) primary cosmic rays.

This is accomplished by pumping sediment through a continuous 150 kG magnetic field capable of accelerating monopoles through a scintillation detector system and focussing them into an iron collector target from which they can be re-extracted and re-detected.

II. THE INITIAL APPARATUS

The initial search was conducted with a refined version of the apparatus and technique described by Goto, Kolm, and Ford[9], shown schematically in Fig. 1. It consists of a cylindrical track plate camera installed inside a 5 cm caliber Bitter solenoid magnet generating a central field of 100 kilogauss, the variation of the on-axis field being indicated in the figure. The specimen is located in a 12 mm diameter polyethylene capsule at the magnetic center. North and South monopoles are extracted in opposite directions and pass through separate nuclear emulsion sandwiches inclined at an angle of 27° with respect to the magnetic axis. They are then re-trapped in iron powder collector targets one inch thick, from which they can be re-extracted and re-detected. The apparatus in its original form has two basic shortcomings: it can only be used to search small quantities of material, and it gives no assurance that the monopoles are accelerated to maximum energy since they may be extracted before the magnetic field has reached its full value. The lower limit of field required to extract a singly charged Dirac monopole from iron, calculated on the basis of macroscopic considerations[9], is 53 kilogauss; it depends logarithmically on charge, increasing to only 57 kilogauss for a doubly charged monopole and to 67 kG for a monopole of charge 12. The extraction field for ferromagnetic minerals of lower saturation than iron, such as magnetite, is typically only

16 kilogauss. Monopoles contained in ocean sediment are presumably trapped in the cosmic spherules present in all sediment[21, 22], and these are essentially meteoritic iron. When searching materials of lower saturation, iron "slingshot" plugs were installed at either end of the sample capsule to retain prematurely extracted monopoles until the field had reached at least 53 kilogauss.

Both of the above shortcomings were eliminated in a modified version of the original apparatus, shown in Fig. 2. In this apparatus the field remains constant at 100 kilogauss (later increased to 150 kilogauss), and material to be searched is introduced and removed along the field axis. Sediment was pumped in the form of a 30% to 50% solid slurry at the rate of 24 liters/minute through the concentric tube arrangement shown in the figure, which terminates in a .37 mm thick bronze window located at the magnetic center. Solid materials such as meteoritic iron and magnetite were introduced in a polyethylene capsule attached to the end of a ramrod. Only monopoles of one polarity can be extracted at a time in this modified apparatus; their anti-poles remain in the slurry upstream of the intense field region when the slurry tube is used, but would be lost when searching solid specimens. The field direction was therefore reversed before the termination of each slurry run, and all solid specimens were divided into two halves, one being searched for north and the other for south monopoles.

The nuclear emulsions were prepared, processed, scanned and analyzed by Herman Yagoda, Robert Filz and their collaborators at the Air Force Cambridge Research Laboratory in Bedford. The basic emulsion was 600 micron thick Ilford G-5 pellicle, sandwiched between two identical pellicles from the time of its manufacture in England until the time of its installation in the apparatus. The control pellicles served to achieve a certain amount of background rejection by identifying the vast majority of unwanted tracks. In some of the last experiments using this method we adopted the use of a "finder" emulsion to facilitate scanning; this was a freshly prepared thin emulsion superposed over the 600 micron emulsion immediately prior to an experiment and processed with a high degree of over-development immediately after the experiment. The background rate, counting all tracks more ionizing than a relativistic proton which penetrated the active beam area, turned out to be about one per hour.

It has been assumed in all previous studies that monopole tracks in emulsion are unambiguously identifiable on the basis of predicted characteristics[23]. At relativistic energies they are expected to ionize as heavily as a relativistic particle carryi ng an equivalent electric charge, ~ 68, and near the end of their range they are expected to exhibit a constancy of ionization which is in marked contrast with the terminal broadening of electrically charged particle tracks. This predicted difference is based on the circumstance that an electric particle is surrounded by a constant electric field and ionization probability increases linearly with exposure time as the particle comes to rest; the electric field surrounding a monopole on the other hand decreases linearly with its velocity, thus offsetting the increasing exposure time, until the electric field no longer suffices to ionize emulsion atoms. The monopole is therefore expected to stop ionizing more or less abruptly and to continue along its path without leaving a track[24].

A relatively small fraction of the total material reported here was searched by the method described above, before the use of nuclear elusions was abandoned. This material included sediment, magnetite from the ocean floor as well as surface outcrops, about one kilogram of iron chips from the Carbo meteorite[26], and some specimens of stony meteorite. In all of this work, four emulsion tracks were obtained which satisfied all monopole criteria except specific ionization (or track width), and which shared certain peculiarities. One of these tracks terminated in the emulsion, which makes it particularly interesting. A micrograph of this track, as well as its measured geometry is reproduced in Fig. 3. The track is 1850 microns long and slightly heavier than observed terminal alpha tracks, and would correspond to a total energy loss of 70 Me V if it were an alpha particle. It exhibits excessive multiple scattering, and shows no significant variation in density over its entire length (as determined by gap count and width measurements). It lacks any terminal broadening. The track falls within the acceptance angle for a south monopole trajectory and was produced during the period of two days in which the emulsion was installed in the apparatus and exposed to a search of sediment from the north and south Pacific (see first item listed in Table 1). On the basis of predicted characteristics, a monopole track should have been at least 5 microns in width (note micrometer scale shown in micrographs). Herman Yagoda concluded on the basis of extensive quantitative analysis that the track is unlike any other track he had ever examined. Another noted expert, on the other hand, P. H. Fowler[27] concluded that the track is not incompatible with a He^3 nucleus coming to rest.

Positive identification of a monopole could, of course, be made regardless of track characteristics if it were possible to re-extract it from the iron collector target and reobserve it. With the best time resolution achievable by the use of track plates (about 10 minutes), and our background of 1 track per hour, the probability of one geometrically acceptable monopole track, regardless of track characteristics, is 2%. Thus the probability of two re-extractions is 8×10^{-6}, which can be regarded as conclusive evidence. Unfortunately the negative re-extraction results we obtained are not comparably conclusive. Due to the divergence of the magnetic field and the limited angular aperture of the solenoid magnet, the iron collector target intercepted only about one third of the monopole beam at best. If monopoles are assumed to lose a substantial fraction of their energy in the emulsion, the target intercepted substantially less of the beam.

Two improvements in technique were obviously necessary: improved control of the monopole trajectory to ensure trapping, and improved time-resolution of the detection process. Since track characteristics evidently fail to permit positive identification of a single event, the tedious and time-consuming work of emulsion scanning hardly seems justified. It was therefore decided to rely on the use of multiple scintillation detectors in the final version of the apparatus.

III. THE FINAL APPARATUS

The final apparatus incorporates two fundamental modifications: the use of scintillation counters to permit immediate identification of a single monopole event against an insignificant background, and better control of the magnetic field geometry to ensure a high probability of re-trapping. Three or even two successive observations of a single retrapped monopole with the time resolution of a counter system would provide convincing evidence regardless of the ionization characteristics observed.

The apparatus is shown schematically in Fig. 4. The Bitter solenoid magnet generates a continuous field of 150 kilogauss at the center, the variation of axial field being indicated in the figure. Sediment is introduced along the magnetic field axis through a 1.25 cm diameter copper tube terminating in a 1.25 cm diameter phosphor-bronze window .04 cm thick. The sediment then exits in the reverse direction through a surrounding coaxial outlet tube. Provisions are made to purge a plug of ferromagnetic material which occasionally collects at the window. Sediment is handled in the form of a thick slurry (30%-50% solid) by a peristaltic pump at a rate of about 400 cm^3/sec.

After passing through the bronze window, a monopole finds itself in a partially evacuated beam tube at a point of converging magnetic field, 8.1 cm before reaching the magnetic center. The trajectory of the monopole is governed predominantly by the initial field direction. The subsequent influence of the radial field component on the monopole's trajectory depends of course on the monopole mass: a heavy monopole injected at the periphery of the window will continue a converging path, cross the field axis and diverge in the opposite direction. The lighter a monopole, the later it will cross the field axis. Monopoles of a certain mass satisfy focussing conditions and approach the field axis asymptotically. Monopoles below focussing mass approach the field axis at first, and then diverge. Monopole trajectories for a range of mass values were determined by means of a computer program formulated by E. M. Purcell of Harvard University. The program makes an incremental calculation of the worst trajectory, one starting at the periphery of the window, and takes into account the off-axis field of the solenoid. At the selected location of the injection window, monopoles of mass up to 1.4×10^4 g_{Dirac}/g times the proton mass would have traversed all detectors and been trapped.

Travelling down the beam tube, monopoles leave the high field region and then pass through four plastic scintillation counters each 0.25 mm thick, followed by a tank of liquid scintillator containing four iron barriers which are magnetized by means of surrounding coils in the appropriate direction for monopoles being collected. Five photomultipliers monitor the liquid scintillator between iron traps. Partial evacuation of the beam tube minimizes scattering, while leaving enough gas molecules to ensure stripping of any atoms losely bound to the monopole. Before coming to rest in the first target, the monopole will trigger a five-fold coincidence: $S_1S_2S_3S_4T_1$ (Fig. 4). Having acquired 52 GeV of kinetic energy (assuming Dirac charge), the monopole will stop within the trapping tank, which contains 25 g/cm^2 of liquid scintillator and 55 g/cm^2 of iron. If the monopole is stopped in the liquid, the weak polarizing field >100 gauss generated by coils surrounding the chamber will ensure its being trapped in the next collector, rather than being swept upward or downward by the earth's field.

Two anti-coincidence counters, A_1, A_2 are placed below the vacuum drift tube to reduce the cosmic ray counting rate. The lead shielding (about 10 radiation lengths) sufficient to stop delta rays produced by collisions of a monopole as light as a fraction of a proton mass.

The five-fold coincidence $S_1S_2S_3S_4T_1\bar{A}_1\bar{A}_2$ triggers a 517 Tektronix oscilloscope where all the nine counters are presented and photographed.

IV. CALIBRATION AND BACKGROUND OF THE EXPERIMENTAL APPARATUS

The five-fold coincidence $S_1S_2S_3S_4T_1$ is timed by a Sr^{90} source, the range of its 2.26 MeV electrons being sufficient to traverse the four plastic counters and leave enough residual energy to register in T_1. The high voltage plateau of the counters is made with the same Sr^{90} source. Each counter, at plateau, has an efficiency for minimum ionizing particles of more than 80%.

The other liquid counters are timed by light emitting diodes, using T_1 as reference. Fine timing is not necessary on these counters since they do not enter into the trigger logic.

When the high voltage on each counter is set to its plateau value, an α-source (Po^{210}) is brought in contact with the plastic counters S_1-S_4. The α-particles lose all their energy ($\sim$ 5 MeV) in the plastic. A monopole will lose 80 MeV. Although the ratio of the energy loss of the α-particle to the monopole is 1:16, we expect the pulse height output for monopoles to be approximately 3 times larger than α-particles because of plastic scintillator saturation and because of non-linearity of the photomultipliers. Appropriate attenuators are inserted in the presentation chain to keep α-particle pulse height to 1 cm on the scope. The pulse from the liquid is also set at 1 cm on the Tektronix scope for cosmic rays.

The phototubes are shielded from the stray magnetic field of the solenoid. The effectiveness of shielding is checked by light diodes, i.e., observing pulse output and timing with and without magnetic field. Under the conditions described above, the counting rate due to cosmic rays not rejected by the two anti-coincidence counters is 0.2 per hour. Finally we want to emphasize the fact that the criterion for identification of monopoles is not only the presence of a five-fold coincidence with large pulses. We also require that the monopole be trapped, and be re-extracted from the iron trap when it is inserted into the magnet in place of the slurry. During an early trial run we observed a monopole candidate according to pulse height criteria, but it failed to satisfy the trapping criterion. Probably the large pulse height was due to Cerenkov light generated in the counter's light pipes by a reasonably dense cosmic ray shower. It was this observation which indicated the need for anti-coincidence detectors and a more sophisticated trapping arrangement.

V. DETECTION LIMITS OF THE APPARATUS

The apparatus is capable of detecting monopoles within certain limits of mass and magnetic charge, illustrated in Fig. 5. The limits are imposed by three separate conditions: focussing, range, and time-of-flight.

The focussing condition requires simply that the monopole follow a trajectory which intersects all scintillators and trapping barriers. As explained above, the injection window was located at a point of converging magnetic field, chosen so as to optimize range of monopole mass for which focussing is ensured. The acceptable mass range extends from zero to $1.4 \times 10^4\ g_{Dirac}/g$ proton masses.

The range condition requires that the monopole traverse at least the four scintillators in the evacuated tube and the window leading into the liquid scintillator tank, and that it be stopped within the four iron collecting barriers located in this tank. The energy gained by the monopole in traversing the magnetic field is proportional to charge, while its energy loss rate in traversing matter is proportional to the square of the charge. The permissible range of monopole charge extends from 0.16 to 27 times the Dirac charge.

The time-of-flight condition is related to the time resolution of the coincidence $S_1S_2S_3S_4T_1$, which is 20 ns full-width, half-maximum. The distance between S_1 and T_1 is 65 cm, and therefore particles of velocity lower than 0.1 c will fail to register as a coincidence. This corresponds to a mass limit of $10^4\ g/g_{Dirac}$ proton masses.

VI. RUNNING PROCEDURE

The slurry is pumped through the magnetic field at a rate of 400 cm^3/sec. When all the sample has been searched for monopoles of one polarity, the field is reversed, both in the Bitter solenoid and in the trapping chamber, and the sample is pumped again to search for monopoles of the opposite sign. During the analysis of the samples listed in Table 1, no five-fold coincidence satisfying at least the pulse height criteria was registered.

VII. FLUX AND CROSS SECTION LIMITS

The negative result of this search provides a basis for establishing an upper limit on the arrival rate of monopoles, both primordial and generated in the upper atmosphere, whose energy was sufficiently low to permit trapping in the material searched. It is also possible to deduce an upper limit on the production cross section of monopoles due to high energy proton collisions with nuclei in the upper atmosphere.

The material searched, which is identified precisely in Table 1, can be divided into five categories: there are four groups of deep sea sediment, each characterized by a different sedimentation rate[14], and the magnetic component extracted from a clay deposit, which must be treated separately.

The four groups of deep sea sediment represent the following volumes V and sedimentation rates S:

$V_1 = 6.6 \times 10^5 \text{ cm}^3$ $\quad S_1 = 1 \text{ cm}/10^4 \text{ years}$

$V_2 = 1.1 \times 10^4 \text{ cm}^3$ $\quad S_2 = 1 \text{ cm}/2.5 \times 10^4 \text{ years}$

$V_3 = 1.1 \times 10^5 \text{ cm}^3$ $\quad S_3 = 1 \text{ cm}/10^4 \text{ years}$

$V_4 = 5.4 \times 10^3 \text{ cm}^3$ $\quad S_4 = 1 \text{ cm}/2 \times 10^4 \text{ years}$

The total area-time product (or intercepted flux) for these four samples is:

$$AT = 2.5 \times 10^{17} \text{ cm}^2 \text{ sec.}$$

The sediment was obtained at an average depth of about 4400 meters, or a thickness of 4.4×10^5 gms/cm^2 for stopping monopoles (at vertical incidence).

The Georgia clay deposit has been under 15 meters of water for 5×10^6 years. It was formed by the pulverization of local granite and contains an average of 1% of uniformly distributed paramagnetic impurities of colloidal size consisting largely of titanium oxides. A reasonable assumption for the mixing depth due to earth convulsions is 100 meters, which corresponds to a "sedimentation rate" of

1 cm/500 years. A total of 10^6 cm^3 of magnetic component was extracted at a mining operation by magnetic filtration and transported to Cambridge, representing a search volume of 10^8 cm^3. The clay sample thus corresponds to an area x time product of

$$AT = 1.5 \times 10^{18} \text{ cm}^2 \text{ sec}.$$

The density of clay is 2.5, and the mixing depth of 100 meters is therefore equivalent to a thickness of 2.5×10^4 gms/cm^2 for stopping monopoles (at vertical incidence).[28]

Since all deep sea sediment is pervaded with ferromagnetic material in the form of "cosmic spherules" of meteoritic iron[21, 22], the collection efficiency can be assumed to be 100% for all monopoles of range R less than the ocean depth d. For more energetic monopoles, the collection efficiency is $\frac{d}{R}$, a result which is readily obtained by integration over the hemisphere. The same assumption applies to the collection efficiency of the clay, providing all monopoles were in fact trapped by the magnetic component and extracted during magnetic separation. Since the impurities are only slightly more magnetic (0.08 emu/gm saturation magnetization) than the clay itself (0.02 emu/gm), the argument is not as convincing in the case of clay as it is in connection with the deep sea sediment.

To obtain an estimate of the collection efficiency for monopoles created in the atmosphere, we note that the differential spectrum of primary protons falls rapidly with primary energy, and production will therefore occur predominantly at energies slightly above threshold. This of course assumes that the cross section is not a sharply rising function of the energy. If the above assumption is correct, then the incident proton energy must be divided into at least three parts: the scattered proton and a pair of monopoles. Thus if the average incident energy were three times E_{th} and the energy were divided equally into three parts, the monopole energy should be approximately equal to E_{th}.

The number of primary cosmic rays with energies greater than E is given by [30]

$$N(>E) = E^{-1.6} \text{ protons/cm}^2 \text{ sec sr for } 10 \leq E \leq 2 \times 10^6 \text{ GeV}, \quad \text{and}$$

$$N(>E) = 8 \times 10^3 \times E^{-2.2} \text{ protons/cm}^2 \text{ sec sr for } 2 \times 10^6 \leq E \leq 2 \times 10^9 \text{ GeV}.$$

Since we do not know the energy dependence of the cross section, we shall assume that the cross section is constant from E_{th} to ∞. We assume also that monopoles are created only in primary collisions and not in secondary collisions by outgoing pions.

VIII. RESULTS AND CONCLUSIONS

The results of the present search are presented in three figures: Figure 5 depicts the detection limits of the present experiment by showing the envelope of monopole mass versus monopole charge within which detection would have been assured. Fig. 6 shows the upper limit of monopole flux as a function of arrival energy established by the present search as well as the limits of the recent search of lunar material [20] based on an assumed mixing depth of 5 cm and 100 cm. Fig. 7 shows the upper limits of monopole pair production cross section as a function of monopole mass established by the present search, the lunar search and the search of deep sea sediment by Fleischer et al. [18, 19].

Searches to date have established that the arrival of monopoles, whether primordial or secondary, is a rare event by human standards, and any real-time search of cosmic radiation is pointless. According to the present search, as well as that of Fleischer et al.[18,19], the arrival of monopoles is rarer by two orders of magnitude than that of extensive air showers, and it is therefore possible to state, as the only positive result of monopole research, that monopoles are not responsible for the generation of extensive air showers.

It is useful to obtain an intuitive understanding of the effectiveness of the present search. We would have detected only monopoles arriving with energy below 5×10^{8} GeV. At the energy limit we would have detected an arrival rate greater than 5×10^{11} monopoles per year over the entire earth. This upper limit of arrival rate decreases with energy down to 10^{5} GeV, and below this arrival energy we would have detected an arrival rate of only 10^{9} monopoles per year per earth. For comparison, the arrival rate of meteorite falls (that is, meteorites large enough to be found) is about 500 per year per earth. The incidence of meteorite falls is cited only as a standard of rarity, and not to imply any relation to monopoles. The comparison allows us to state that the present search for monopoles is less effective by a factor of 10^{7} to 10^{9} than a search for objects detectable by the human senses.

The arrival energy of monopoles is likely to be about three orders of magnitude above our energy limit. Since there is no presently conceivable way to increase this energy limit, the only possible way to improve the effectiveness of our search is to extend it to substantially larger quantities of terrestrial material in the hope of detecting monopoles in the low energy tail of their energy distribution. If Osborne's conclusions concerning the upper limit of monopole flux are correct[13], the search will have to involve several cubic kilometers of material.[31]

The experiment is founded on three basic assumptions: that a monopole is indeed trapped, that it can in fact be extracted, and that it can be reliably detected. The validity of the trapping assumption appears to be above doubt for the deep sea sediment, since all that is required is that the monopole stop in the sediment. In the case of the Georgia clay, the monopole may not have been collected by the magnetic filtering as mentioned in section VII. However, the Georgia clay does not contribute to the flux limit at high energies, and hence to the cross section limit at high masses.

The extraction hypothesis, on the other hand, requires some qualification. Although trapping energy is certainly no lower than suggested by the macroscopic interaction, it may be higher due to some local interaction or nuclear polarization.[32] Even if the monopole were tightly bound to a sphere of atoms of 10 Angstrom radius, this would not preclude extraction. As has been previously pointed out[9], a magnetic field of 100 kiloersted intensity provides adequate force on a monopole of Dirac charge to move the entire cluster through any solid material. Once extracted detection seems assured inasmuch as the experiment requires that the monopole produce ionization only several times that of a relativistic proton. In section V, it is stated that monopoles with charges down to 0.16 Dirac charges would have been trapped by the iron barriers in the liquid scintillator. Monopoles of charge down to 0.04 Dirac charges would not have been trapped, but would have given very large pulses in all of the counters. We saw no events of this type. If a monopole was bound to a nucleus [32], it would be extracted with the nucleus but might not be detected because the presence of additional energy loss would modify the range detection limits (Fig. 5). An estimate of this alteration using a monopole bound to an iron nucleus show a change in the high mass boundary of the detection limits for small monopole charges. For example for $g = g_{Dirac}$ the limit in mass is reduced from $\sim 6000\ m_p$ to $\sim 3000\ m_p$.

The experiment used by Alvarez et al. in searching lunar material[20] detects monopoles without extraction by passing the sample repeatedly through a superconducting solenoid. Although this method is not as well suited to the search of substantial quantities of material as the present technique, it may be worth adapting to the purpose in order to avoid dependence on the extraction hypothesis. An expedient way to accomplish this would be to transfer monopoles by direct contact from the dredged material into a small collector by means of a superconducting magnet at the dredging site, and to pass the small collector through the superconducting detector.

The next stage of progress in the search for the monopole is likely to be experiments upon completion of the National Accelerator Laboratory.[33,34,35,36] According to an argument advanced by Ruderman and Zwanziger[10] mentioned in the discussion of rationale, monopole pairs may recombine immediately after creation unless they are created with a very substantial amount of kinetic energy. If recombination is their fate, they may manifest themselves only as resonant state, probably annihilating into several photons. This possibility has been taken into consideration in planning one of the NAL experiments.

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24. These predictions appear very convincing at a superficial level, but we believe that they must be accepted with serious reservations. The simplified model, for example, does not even account for observed differences in the range of positive and negative pions[25]. The solenoidal electric field surrounding a monopole's path together with its very intense radial magnetic field might conceivably produce substantially different emulsion tracks. Furthermore, if a monopole were strongly bound to a moderately heavy nucleus, the ionization produced by the system would be difficult to distinguish from a somewhat heavier nucleus alone. The characteristics of emulsion tracks are subject to such statistical variations as to make the process of single track analysis a highly subjective art. We found that the most sophisticated quantitative methods of analysis applied to single event tracks can lead to contradictory conclusions in the hands of different experts.

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28. Our estimate of the energy-range relationship for monopoles is based on the calculations of K. Kobayadawa[28] for high energy muons. These result in an expression of the form:

$$-\frac{dE}{dx} = a + bE,$$

where a is the ionization loss in $GeV/gm/cm^2$ and b is a term representing the sum of energy loss due to bremsstrahlung, pair production and photo-production (assuming that the monopole does not have direct strong interactions). However, these corrections to the energy-range relationship appear to be of the order of 10-20%. The models used for calculating the correction have an uncertainty far greater than 10-20%. We therefore neglect the contribution due to the other energy-loss mechanisms and use a constant energy-loss of 9.4 $GeV/gm/cm^2$.

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31. An expedient approach to accomplishing this would be to search the vast quantities of sediment which are being continuously dredged from the delta of the Mississippi River by the U. S. Corps of Engineers. The use of a superconducting extraction magnet makes such a project quite feasible; it would be more promising than a continued search of the very small quantities of deep sea sediment which are available.

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TABLE I

Material Searched for Monopoles

Source	Latitude	Longitude	Depth Meters	Volume cm^3	Specimen
British	7°25'S	152°15'W	5030	0.8	sediment
Museum	13°28'S	149°30'W	4300	1.35	sediment
Natural	22°21'S	150°17'W	4370	1.75	sediment
History	32°36'S	137°43'W	4350	2.85	manganese nodules
Dr. J.	same	same	same	1.95	sediment
Wiseman	33°29'S	133°22'W	4275	1.75	sediment
	same	same	same	2.45	manganese nodules
	25°39'N	52°58'W	5540	2.55	sediment, core
	19°21'N	62°07'W	7800	3.15	sediment, core
Woods Hole	0°15'S	18°35'W	5500		radiolarian ooze
Oceanographic	20°00'N	66°36'W	5120		magnetite
Institute	20°57'N	66°15'W	5120		sediment, pipe dredge
Dr. Peter	20°10'N	66°09'W	5760		sediment
Sachs	1°23'S	29°49'W	4000	$8x10^3$ total	magnetite
Scripps	32° N	126° W	3660	$6.6x10^3$	5 separate piston
Institution					cores, sediment
of	25°11'N	149°21'E	5451	$2.2x10^5$	sediment, dredge
Oceanography	29°14'N	144°30'E	4975		
Dr. Chris	30°12'N	143°17'E	5080		
Harrison	20°32'N	114°58'W	3703	$4.4x10^5$	sediment, dredge
University	43°37'N	12°49'W	5278	$1.6x10^2$	sediment, core
of	43°36'N	12°58'W	5230	"	"
Cambridge	43°42'N	12°40'W	5030	"	"
Dr. Davies	43°42'N	12°40'W	5030	"	"
	43°42'N	12°40'W	5033	"	"
	43°43'N	12°36'W	5030	"	"
	41°27'N	14°59'W	5079	"	"
	43°20'N	22°19'W	2774	"	"
	14°39'S	63°49'E	unknown	"	"
	02°55'N	56°35'E	unknown	"	"
	47°46'N	7°42'W	1050	$9.2x10^3$	sediment, dredge
Scripps Institution of Oceanography Dr. John Sclater	25°30'N	133°05'W	5800	$1.14x10^5$	sediment, dredge
University of Miami Dr. Mahlon Ball	17°55'N	65°06'W	4200	$5.43x10^3$	sediment, cores
	10°38'N	65°36'W			

Table I, Cont.

Source	Latitude longitude	Depth Meters	Volume cm^3	Specimen
J. M. Huber Corporation Kaolin Mine Dr. Joseph Iannicelli	Georgia and vicinity clay deposits	unknown	1.025×10^6	magnetic impurities removed from kaolin about 1%.
Harvard University Dr. C. Frondel	Carbo Meteorite		2×10^2	iron shavings

Figure Captions

1. First version of nuclear track plate camera for monopole detection.
2. Second version of monopole detector for continuous search.
3. Measured geometry and micrograph of a monopole candidate track.
4. Final version of monopole detector based on scintillation coincidence of minimum ionizing particles and re-extraction from iron collector barriers.
5. Detection limits of the final apparatus.
6. Upper limit of monopole flux (cm^2 sec) versus incident energy (GeV).
7. Upper limit of monopole pair production cross section (cm^2) versus monopole mass (M/m_p).