Search for Heavy Magnetic Monopoles

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The discovery of an apparent breakdown in time-reversal invariance in $K^0$ decays demands further investigation into the symmetry properties of the fundamental interactions. Since a simple model of electric charge and magnetic poles leads to an electrodynamics which is not time-reversal invariant, it appeared essential to extend previous investigations concerning the possible existence of magnetic monopoles to regions of higher monopole mass and lower production cross section. An experiment was designed to detect monopoles produced in the earth's atmosphere by the primary cosmic radiation following a method introduced by Maltus. A solenoid with a magnetic moment of $3 \times 10^9 \text{ A m}^2$ was used to collect monopoles moving along the earth's lines of magnetic flux and to accelerate them through scintillation counters, a spark chamber, and into emulsions. The negative results of the search show that the monopole flux at the surface of the earth is less than $10^{-9} \text{ cm}^2 \text{ year}$. Using for the sake of comparison, a simple model of monopole production such that the cross section is constant above threshold, this result shows that the cross section for the production of monopoles by nucleon-nucleon interactions is less than $10^{-9} (b/Mc)^2$ for a monopole mass $M$ of 15 BeV/$c^2$. The limit on the production of monopoles by photonucleon interactions is about $10^6$ times higher. In both cases the cross-section limit varies with monopole mass approximately as $M^{1.4}$.

1. INTRODUCTION

A SYMMETRY of Maxwell's equations with respect to $B$ and $E$ appears to be marred by the presence of electric charge and the apparent absence of magnetic monopoles in nature. Further the observed discrete character of electric charge is not a consequence of Maxwell's equations but appears as a separate and unconnected property. In 1931 Dirac suggested that a partial answer to the symmetry problem together with some insight into the question of the origin of the particular character of electric charge could be provided by postulating the existence of a magnetic monopole. Using a certain approximation to a complete expression of quantum electrodynamics (essentially a first quantization theory), he was able to show that the product of any electric charge $e$ and any magnetic pole strength $g$ must be equal to $\frac{1}{2} nh\epsilon c$, where $n$ is an integer. Such a relation clearly demands that if both charges and poles exist there must be a smallest value for each. The existence of monopoles would then supply a natural basis for the quantization of electric charge.

The suggested symmetry between electrical and magnetic effects is not perfect, however; since the measured value of $\epsilon^2$, where $\epsilon$ is the electronic charge, is $(1/137)\hbar c$, the value of $g^2$ is at least as large as $(137/4)\hbar c$—the smallest magnetic charge must be very much larger than the electronic charge. Furthermore a universe which contains both electric charge and magnetic poles will not have simple symmetry properties if the poles have the same transformation properties that we ascribe ordinarily to charge. The electromagnetic field will not, in general, be invariant with respect to space inversion $P$, or time reversal $T$. It may well be invariant under the combination $PT$.

The noninvariance of the interaction under space inversion is illustrated in a simple manner by a consideration of the interaction represented in Fig. 1. In Fig. 1(a) we see the path of a positive charge near a plane carrying a North magnetic pole density, together with the mirror reflection. We use the "mirror" transformation in the place of $P$, or space inversion, since it is easier to visualize. The two transformations differ only by a rotation of 180° about an axis normal to the mirror. The reflected trajectory is not identical in character with the original trajectory. A rotation and translation cannot transform the two results into one another. It is clear that a left-hand or right-hand coordinate system is defined by the interaction. Two laboratories can standardize their coordinate conventions if they exchange sets of positive charges and North poles and a description of this fundamental interaction. It is evident that parity is not conserved.

In Fig. 1(b) we see the same interaction together with the interaction viewed with time reversed. The results are again different in that the two results can not be brought into coincidence through rotations and translations. Therefore the direction of time could be determined by observing the interaction independent

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characteristic electromagnetic contributions to the
masses of charged particles are of the order of the mass
of the electron or greater we can expect that the elec-
 tromagnetic contribution to the mass of the particles
carrying a pole will be greater by the ratios of the
squares of the charges. Then $M$, the mass of such a
monopole, would be expected to have a magnitude near
to $n^2(137/2)^2m$, where $m$ is the mass of the electron
and $n$ is the Dirac quantum number. This mass, which
is about equal to $2.4n^2$ BeV/$c^2$, is of course only a sensible
guess of the possible magnitude. Even as the strength
of a monopole is much different than the charge of
the electron, a particle carrying a monopole charge may
be very different in other ways. Though the monopole
mass may be larger or smaller than $2.4$ BeV/$c^2$, the
mass will probably be quite large. We might then expect
that any peculiar character of the electromagnetic
field would manifest itself only at energies (or better,
four-momentum transfers) such that virtual monopole
pairs would be important. This will occur only at four-
momentum transfers of a magnitude near the monopole
mass, and this region has not been carefully explored.
Though any complete electrodynamics almost surely
will be quite different from our present quantum
electrodynamics, we might expect that some corre-
sondance principle must remain so that for small
momentum transfers, where monopole effects would not
be important, the complete formulation would reduce to
the present system.

This would still be insufficient to make the concept
of monopoles attractive to many observers except
that there now exists an indication that the symmetry
properties required of interactions in general are not
so simple as we had believed. The anomalous decay of
the $K^0$ meson strongly indicates that the interaction
involved in the decay is not invariant under time re-
versal. Furthermore, the ratio of the amplitude which
is not time-reversal invariant to the time-reversal-
invariant amplitude is very nearly equal to $(1/\pi)$
$(1/137)$. Following the view of Lee, if we accept direc-
tion from the Gell-Mann–White axiom: “Everything
which is not forbidden is compulsory,” we are led to
suspect that the breakdown may well result from a lack
of time-reversal invariance in the electromagnetic
interaction. If the electromagnetic interaction is indeed
much more complicated than we have been led to
believe, our aesthetic reasons for discarding the con-
cept of monopoles not only vanish, but the concept of
the existence of the monopole might even be considered
as an attractive simplification.

Previous experimental searches for monopoles can
be separated into two general categories. The first of

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2. EXPERIMENTAL DESIGN AND APPARATUS

Monopole pairs are assumed to be produced when the high-energy cosmic-ray nucleons collide with nucleons in the atmosphere. Explicit models for this production will be considered later. Typically, the production interaction is expected to occur at 10 to 15 kilometers above the earth's surface. Because of their large electromagnetic interaction strength, monopoles should lose their energy quite rapidly and become thermalized in the atmosphere. Previous calculations show that the energy loss of monopoles with magnetic charge $g = [(137/2)\hbar c]^1/2$ is $8 \text{ BeV/(g cm}^2)$, or about $10 \text{ MeV/cm}$ at sea level.\(^4\) The monopoles would feel a force due to the geomagnetic field but would not be accelerated since the energy gained from a magnetic field is only $20 \text{ MeV/KG}$ cm and the energy loss in passage through the atmosphere is many orders of magnitude greater than the energy extracted from the earth's field of $0.6 \text{ G}$. We should then expect the monopoles to diffuse slowly along the geomagnetic field lines.

The apparatus used to collect and detect monopoles is shown schematically in Fig. 2. The solenoid essentially "gathers in" the geomagnetic field lines over an effective area of $1600 \text{ m}^2$. The total sensitive area of $1600 \text{ m}^2$ was calculated according to the following argument based on the continuity of magnetic-field lines. For simplicity, assume that the earth's field is of constant magnitude and normal to the surface. The situation with the solenoid turned on is illustrated in Fig. 3. Since the solenoid field is aligned with the earth's field in the core, the fringing field will be opposing the earth's field. Thus there will be some radius in the median plane where the two fields just cancel: we call this radius $R_e$. It is clear from the continuity of field lines that all the geomagnetic lines within a cylinder of radius $R_e$ must pass through the core.

In addition, the "missing flux" beyond $R_e$ must have also gone through the core as a consequence of the continuity of field lines. The missing flux is defined as the difference between the flux with the magnet off and the

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The solenoid coils were borrowed from the 14-in. bubble-chamber magnet at the Brookhaven National Laboratory Cosmotron. They consist of 12 pancakes, each containing 32 turns of water-cooled copper. The coils were arranged in two stacks of 6 pancakes separated by 15 in. In this configuration, the coils have an over-all length of 1 m, a core diameter of 17 in., and an outside diameter of 38 in. During the experiment, a current of 5000 A was run through the coils, expending a megawatt of power and giving a total of $1.92 \times 10^6$ ampere-turns. A 9-ton column of steel, placed under the coils, increased the magnetic moment of the system by about 17%. The total magnetic moment was $1.3 \times 10^9$ G cm$^3$ with a peak field of 13 kG.

The detection system consisted of 3 scintillation counters, a spark chamber, and a rack of nuclear emulsions.

Scintillation counters $C_1$ and $C_2$ were operated in coincidence to trigger the spark chamber when a monopole emerges from the magnet core. Since a monopole will ionize about 4000 times stronger than minimum, we expect a characteristic huge pulse from the scintillator.

However, empirical studies of organic scintillators for heavily ionizing particles have shown a saturation effect on light output. If we extrapolate their empirical relations, we expect a pulse of about 100 times minimum. It was decided to set the discrimination level at 30 times minimum, so that we were insensitive to single electrical charges. The discrimination level was calibrated by setting the electronics to be just efficient for counting cosmic-ray muons with another block of scintillator whose geometrical efficiency was 30 times the experimental configuration. During the run, the coincidence trigger rate was checked against the known air shower density spectrum and was found to be consistent with a trigger from 30 minimum particles. The two coincidence counters were constructed of thin (0.33 g/cm$^2$) plastic to minimize the energy loss. The 18-in. x 18-in. scintillators were placed immediately under the magnet to cover the entire core opening, and were separated by 2 in. to reduce the probability of a trigger from particles entering at a grazing angle.

In addition, a third scintillation counter was used in anticoincidence to eliminate triggers from air showers. The counter measured 20 in. x 20 in. and was 1 g/cm thick. It was set to be efficient for a single minimum ionizing particle. The counter was placed above and off to the side of the coils away from the monopole path to reduce the danger of counting a delta ray produced by the monopole. This is a serious problem since a monopole would create more than 200 delta rays with energy greater than 10 MeV and on the average at least one with energy greater than 200 MeV.

\textsuperscript{18} For a review, see F. Brooks, Progr. Nucl. Phys. 5, 252 (1956).

This location should not affect the air shower sensitivity since any shower dense enough to trigger the coincidence counters would cover many square meters.

All three scintillation counters were shielded from the intense magnetic fields by using long light pipes so that the RCA 6810 photomultipliers were approximately 2 m from the peak fields. In addition, the tubes were shielded with about 60 lb of steel. In this configuration, no reduction of photomultiplier gain due to the magnetic field was observable.

The helium-filled spark chamber was used for a rapid scan to identify candidates and to locate the position of candidates in the emulsion. It measured 17 in. X 17 in. and was placed about 10 in. below the bottom of the magnet. Our chamber had four gaps with a 1/2-in. spacing. The plates were 0.020-in. aluminum sheet (total thickness = 0.685 g/cm²) to reduce energy loss. The chamber was pulsed to 15 kV with an over-all delay of 200 nsec. The electronics were gated off for 1 sec after each coincidence to prevent pickup from the spark chamber.

The most conclusive identification of a possible monopole would be in the nuclear emulsion. As discussed in previous papers, the track is expected to be quite heavy—roughly like a fully ionized Z = 68 nucleus. A monopole track should also be distinguished by the property that the ionization is essentially independent of the velocity. Thus the track would be uniform to the end in contrast to the tapering that is characteristic of an electrically charged particle of large charge.

Since background is not a serious problem in our experiment, we chose the moderately sensitive Ilford K-2 emulsion. It is sensitive to particles with ionization greater than six times minimum. We used 1-in. X 3-in. strips of 400-μ (0.15 g/cm²) emulsion. As shown in Fig. 2, the strips were placed on a 20° inclined plane to increase the track length of a vertical monopole.

In summary, the experiment was designed so that monopoles diffusing along those geomagnetic field lines which were pulled in by the magnet would be accelerated through the core and pass through two coincidence counters. This coincidence and the absence of an anti-coincidence count would satisfy the counter logic and trigger the spark chamber. The spark chamber track would serve to locate the characteristic heavy track in the emulsion. Thus any particle which lost more energy than about 30 times the energy loss of a minimum ionizing particle in each of the coincidence counters and gave a spark chamber track consistent with an allowed monopole trajectory and leading to a very heavy emulsion track would be considered to be a monopole. Such a criterion is so stringent that even a single good event would be considered strong evidence for the existence of monopoles.

It is instructive to comment on the sensitivity of this experiment to the mass and number of magnetic charges carried by the monopole. Although production of monopoles is heavily dependent on the mass, the only mass dependence of the detection apparatus enters in the ability to focus very massive monopoles. Figure 4 shows the trajectories of various masses, obtained by integrating the equations of motion. It is clear that masses up to several hundred BeV/c² would be detected if produced.

We noted earlier the Dirac quantization condition, \( \frac{e}{hc} = n/2 \) (Dirac), where \( n \) is an integer. In most calculations it is tacitly assumed that \( n = 1 \) and \( e \) is the electronic charge. We should not exclude the possibility that \( n \) can assume higher values. In particular, if quarks exist, \( n \) would appear to be 3. The energy of acceleration goes as \( n \), but energy loss is proportional to \( n^3 \) so the higher values of \( n \) result in a loss of range. Our detection apparatus is 1.5 g/cm² thick, so the monopole must have at least this range to be detected. With these criteria, \( n = 1 \)- or 2-type monopoles will be reliably detected; \( n = 3 \) (quark) monopoles are marginal, and higher values of \( n \) would be undetected. Recently, Schwinger has re-examined Dirac’s original quantization condition and concluded that it should be \( \frac{e}{hc} = \text{integer} \), or equivalently that Dirac’s quantum number \( n \) must be even. This being the case, we would still reliably detect monopoles with a single (but no higher) magnetic charge provided that quarks do not exist. If quarks do exist and Schwinger’s result is correct, then Dirac’s \( n \) would be at least 6 and our experiment could no longer detect even singly charged monopoles.

Recalling that the canonical mass also varies as \( n^2 \), the values of the canonical mass are displayed explicitly in Table I for the various conditions mentioned above. Using Schwinger’s relation, if quarks exist the monopole might be expected to have a mass so great that the question of their existence would be almost inaccessible to direct experiments.

### 3. RESULTS AND CONCLUSIONS

Four counting rates were monitored throughout the experiment; singles rates from both the anticoincidence (A) and one coincidence (C) counter, plus the coincidence (CC) rate and the rate for simulated monopoles (CCA). Both the C and A singles rates were dominated by tube noise. The average CC coincidence rate was found to be about 2 counts/day, which we attributed entirely to air showers. The simulated monopole (CCA) rate was about 1 count/day. The large ratio of CCA to CC counts indicates the presence of an unanticipated background. In some cases a CCA event produced spark-chamber tracks resembling a shower as if the

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anticoincidence pulse was not registered in the logic. An occasional CCA event could not definitely be attributed to a shower. Some of these counts were undoubtedly spurious, perhaps resulting from the pickup of noise—we occasionally observed a CCA without a CC. This remaining background was less than about 0.5 counts/day. No attempt was made to improve on this background since it provided a convenient daily monitor on spark-chamber performance and did not affect our sensitivity to a true monopole.

Proper spark-chamber performance is essential for identifying a monopole candidate. The spark chamber was tested on cosmic-ray muons and found to operate reliably on these minimum ionizing particles. In addition to the daily monitor from shower counts, test runs were made on muons throughout the life of the experiment to insure that the spark chamber was performing properly.

The spark chamber pictures were scanned for a single vertical track. Since a monopole is so heavily ionizing, as we noted earlier, it will produce a few energetic (10–200 MeV) delta rays. These delta rays might produce faint satellite tracks or perhaps even a small, local shower in addition to the bright heavy monopole track. The principal monopole track would probably be so strong that it would rob any sparks from other minimum ionizing particles. It seems highly unlikely that tracks from any other particle could cause appreciable robbing of a true monopole track. Consequently, we require that the monopole track be seen in all four gaps, but we do not exclude the possibility of observing satellite tracks from energetic delta rays.

Most of the pictures contained no tracks since the camera was advanced periodically to prevent over-exposures. In about 80% of the frames which contained tracks, the pattern was typical of an air shower. On the average there were 3–5 tracks, usually only one or two gaps long. Robbing effects were evident for minimum ionizing particles from showers although it was not uncommon to observe up to 4 sparks in the same gap. A casual record was kept of the location of sparks in the chamber. Because of the long exposure times, small contaminations and imperfections tended to cause the chamber to spark in the same places. The other sparks, which we attributed to shower products, seemed to be randomly distributed throughout the chamber. We observed only one four-gap, single-particle track which was rejected as a monopole candidate because of its curvature.

The experiment ran for almost exactly 1200 h and produced no monopole candidates. Recalling that our collection area is 1600 m², we can report no monopoles in a total area-time integral of \( AT = 6.89 \times 10^{24} \text{cm}^2 \text{sec} \). Thus, we can place an upper limit for the flux of north monopoles in the atmosphere of \( R \leq 3.34 \times 10^{-14} \text{cm}^{-2} \text{sec}^{-1} \) at the 90% confidence level. To facilitate cross-section calculations from cosmic-ray fluxes, we can also express this in terms of a differential flux. Since we accept monopoles which diffuse along geomagnetic field lines we can consider that monopoles produced in any direction by the primary cosmic rays will be accepted by our apparatus. The shielding of the earth is such that our acceptance is essentially hemispheric: we accept a solid angle of about 2π sr. Then the differential flux of monopoles has the upper limit \( R < 5.32 \times 10^{-16} \text{cm}^{-2} \text{sec}^{-1} \text{sr}^{-1} \).

We proceed to estimate an upper limit for the cross section of monopole production in nucleon-nucleon collisions. The primary cosmic-ray integral flux is adequately expressed by

\[
N(E \geq E_0) = 1.4E_0^{-1.47} \text{nucleons/cm}^2\text{sr sec},
\]

where \( E_0 \) is expressed in BeV/c². With our experimental area-time-solid angle, we should expect the total number of nucleons with energy greater than \( E \) which might interact to produce a monopole to be about \( 6.1 \times 10^{24} \text{E}^{-1.47} \). Each of these nucleons will interact with a total cross section of about \( 30 \times 10^{-27} \text{cm}^2 \). However, the nucleons in general lose only about 40% of their energy in each interaction. Thus the number of “useful” interactions is greater than one per nucleon. The improvement ratio is about equal to the ratio of the attenuation length to the mean free path of cosmic-ray nucleons. Using measured values for these, we find an improvement factor of about 1.4, so the total number of nucleon-nucleon interactions with energy greater than \( E \) is about \( 8.5 \times 10^{24} \text{E}^{-1.47} \). For purposes of estimation, we assume a production model where the cross section is constant in energy from threshold to infinity. Using the 90% confidence values for the monopole flux:

\[
\sigma_{\text{flux/nucleon}} = \sigma_{\text{monopole/}}/(30 \times 10^{-27} \text{cm}^2),
\]

where \( E_{th} \) is the threshold energy for production of a monopole pair by nucleon-nucleon collision. From elementary kinematics, \( E_{th} = [2(1+M/m)^2-1]mc^2 \), where \( M \) is the monopole mass and \( m \) is the nucleon mass. The cross section is plotted as a function of mass in Fig. 5.

No adequate method of calculating the monopole production cross section now exists. Indeed, all recent attempts at constructing a consistent theory of monopoles have been unsuccessful. However, we might conjecture that a monopole pair, if formed, would proceed from a virtual photon in an inelastic nucleon-nucleon collision. The monopole vertex of the photon is strong, with strength \( g^2/\hbar c = \frac{1}{2} (137) \).

In fact, just because this coupling is so strong, it would be more realistic to use a much reduced effective strength which recognizes such real effects as vacuum

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18 Y. Pal (private communication).
4. SUMMARY

The direct measurements reported here pertain to the flux of monopoles diffusing along the earth's lines of magnetic flux. Within the limits on the value of the magnetic charge of \( n = 3 \) to which the experiment is sensitive, a limit set by the experimental design, we believe that there is little uncertainty in this limited interpretation of our results. In particular, the results are essentially independent of any details of the interaction of the monopoles with matter.

The relation between the limits placed on the flux at the earth's surface and the limits deduced thereby for the production cross section of monopoles by nucleon-nucleon interactions and by photonucleon interactions appears to be equally well defined for any model which defines the energy dependence of the production cross section with energy. Since the cosmic-ray flux decreases strongly with increasing nucleon energy, many plausible models of the variation of cross section with energy are equivalent in that they suggest that most of the production occurs from the interactions of nucleons, or photons, with energies which are less than an order of magnitude above the threshold energy. If this is the case, the simple canonical model of production which considers that the cross section rises to a constant value, independent of energy, for all energies greater than threshold, gives results which are not grossly different than the more realistic models. Generally, the fluxes are a little larger for a model in which the cross section rises more slowly with energy.

One would like to relate the limits on observed cross sections to limitations on the possible character of monopoles, in particular, limitations on their possible mass. There are considerable uncertainties in such a procedure: there are no very reliable calculations concerning the cross section for production of any heavy particle. However, it seems plausible for essentially dimensional reasons that the cross section might be expected to be of the order of the square of the Compton wavelength of the particles times the fine-structure constant: \( 1/137 \). This implicitly assumes that the production of pairs of magnetic poles will proceed through a virtual photon and that the general competition of other channels is adequately considered by using as a basic length the Compton wavelength of the particle. This is not contradicted by the little statistical information we have from very high energy processes. Since the canonical cross section for monopoles of a mass of 15 BeV/c^2, which we deduce from our results, is about a factor of \( 10^4 \) less than this estimate, it seems
likely to us that monopoles, with a charge \( n \) of less than 4 and a mass less than 15 BeV/c\(^2\), probably do not exist.

*Note added in proof.* Since the monopole flux rates are well-defined measurements not subject to model-dependent interpretations, these rates should be used as a basis for comparison with other cosmic-ray experiments. The upper limit on the rate reported in the present experiment is smaller than that reported by Malkus\(^{22}\) by a factor of 7000, and smaller than the rate estimated by Goto et al.\(^{14}\) by a factor of about 20. In an accelerator experiment, Purcell et al.\(^{5}\) set a cross limit about two orders of magnitude lower than our estimated cross section for 3 BeV/c\(^2\) monopoles. The accelerator proton flux at 30 BeV was 80 times larger than our flux at 30 BeV and above.

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