Search for Heavy Magnetic Monopoles

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The discovery of an apparent breakdown in time-reversal invariance in K_2^0 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 Malkus. A solenoid with a magnetic moment of 3×10^5 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^{-6}/cm^2 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 $10^{-6}(\hbar/Mc)^2$ for a monopole mass M of 15 BeV/c^2. The limit on the production of monopoles by photonucleon interactions is about 10^3 times higher. In both cases the cross-section limit varies with monopole mass approximately as $M^{3.4}$.

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[1] 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 $\frac{1}{2}n\hbar c$, 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.

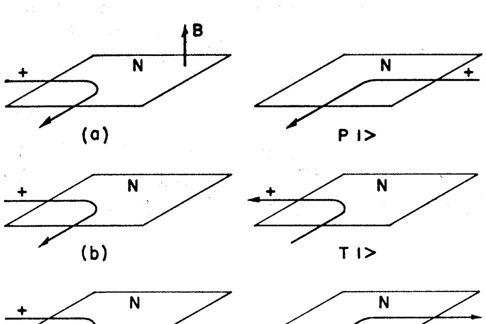

FIG. 1. Monopole reflection symmetry representations. (a) The mirror reflection is not the same as the original state. (b) The time-reversed state is not the same as the original state. (c) The combination of mirror reflection and time reversal can be rotated to coincidence with the original state.

The suggested symmetry between electrical and magnetic effects is not perfect, however; since the measured value of e^2, where e 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

[1] P. A. M. Dirac, Proc. Roy. Soc. (London) A133, 60 (1931).

of information change or entropy change. The interaction is then not invariant under time reversal. In Fig. 1(c) we see the original experiment and the result under time reversal and the mirror transformation. The results are now identical in that they manifestly follow the same rules of behavior—the result transformed by PT can be rotated to coincide with the original experiment. For completeness we note that the interaction is invariant under PC_e, or PC_g, or TC_g, or TC_e, but not PC_eC_g or TC_eC_g, where C_e represents electric charge conjugation and C_g magnetic pole conjugation. It may be possible to construct a magnetic pole which is a pseudoscalar and changes sign upon reflection. Whether the pole can be so defined and retain the symmetric relation with electric charge and remain the source of a magnetic field which varies in strength as r^{-2} is not clear to us.

The electromagnetic field produced by assemblies of charges and poles defined as above cannot be described in terms of transformation properties as simply as the field produced by charges or poles alone. In a mixed system the electric field E is not a vector but transforms as a mixture of vector and axial vector even as the field may result from a combination of electric charges and pole currents. Likewise B transforms as a mixture of axial vector and vector. Though the electrodynamics of a universe which contains only poles or only charges can be constructed so that the field quantities have definite transformation properties, in a mixed universe of this character the field quantities will have mixed transformation properties. Furthermore, for reasons which are related to the problems of mixed symmetries, a consistent quantum electrodynamics which includes both charges and poles has not yet been created. Indeed, it seems almost certain that any formulation of quantum electrodynamics which contains both poles and charges must differ in some radical way from the present theoretical framework.[2–5] These requirements, which complicate the whole concept of the electromagnetic field, have seemed to reduce the attractiveness of the monopole concept, which was essentially aesthetic in any case.

The existing experimental information concerning the transformation properties of the electromagnetic interaction would not seem to exclude monopoles though the electromagnetic interaction has certainly been shown to be approximately invariant under space inversion and time reversal for most processes. It seems quite likely that the mass of any particle carrying a magnetic pole will be quite large. The energy stored in an electrostatic or magnetostatic field is proportional to the square of the field strength and then proportional to the square of the magnitude of the charges or poles which constitute the sources of the field. Even as 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 electromagnetic 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 correspondence 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_2^0 meson strongly indicates that the interaction involved in the decay is not invariant under time reversal.[6] 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,[7] if we accept direction from the Gell-Mann–White[8] 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 concept 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

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

[6] J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay, Phys. Rev. Letters **13**, 138 (1964).
[7] J. Bernstein, G. Feinberg, and T. D. Lee, Phys. Rev. **139**, B1650 (1965).
[8] T. H. White, *The Once and Future King* (Dell Publishing Company, New York, 1960), p. 122.

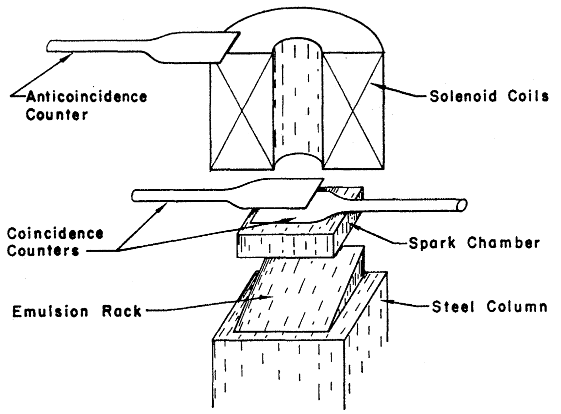

FIG. 2. Schematic experimental arrangement. The apparatus consists of (a) a large solenoid magnet, (b) two scintillation counters C_1, and C_2 in coincidence, (c) spark chamber, (d) emulsion rack, and (e) anticoincidence scintillation counter (A).

these seeks to produce monopoles through the interactions of protons from an accelerator and[9–11] hence is limited by the range of available accelerator energies to the production of monopoles with masses not much larger than the canonical mass of 2.4 BeV/c^2. In this mass region the accelerator experiments are able to set such small limits on the monopole production cross section that it appears unlikely that monopoles with such masses exist. The second class of experiments relies on the interactions of the primary cosmic rays as a source of monopole production. Because of the extremely high energies available (albeit at a much reduced flux), there is no reasonable kinematic limit on the mass of the monopole which might be produced. In the first experiment of this class, Malkus[12] attempted to observe directly the instantaneous flux of monopoles in the atmosphere. This pioneering experiment was limited by its small scale, and the limits on the flux set by this work would not seem to exclude the existence of heavy monopoles. Subsequent experiments sought to take advantage of geological collecting times by extracting monopoles trapped in matter.[13] These extraction experiments rely on various estimates of collection times as well as plausible, but not completely unquestionable, arguments concerning the binding of monopoles to matter.

The experimental situation prior to this experiment may be summarized thusly—monopoles with mass less than the canonical mass of 2.4 BeV/c^2 almost certainly do not exist, but the possibility of the existence of monopoles of mass larger than this is not closed.

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

[10] E. Amaldi, G. Baroni, H. Bradner, H. G. deCarvalho, L. Hoffmann, A. Manfredini, and E. Vanderhaeghe, Nuovo Cimento **28**, 773 (1963).

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

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

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

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 BeV/(g cm^{-2}), or about 10 MeV/cm at sea level.[14] 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 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 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 m^2. The total sensitive area of 1600 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_0. It is clear from the continuity of field lines that all the geomagnetic lines within a cylinder of radius R_0 must pass through the core.

In addition, the "missing flux" beyond R_0 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

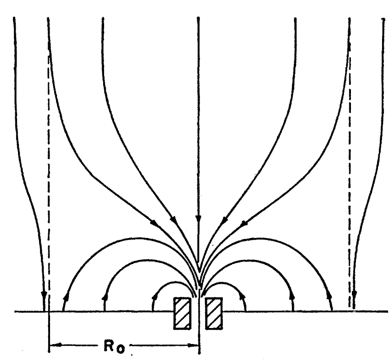

FIG. 3. Sketch of magnetic field for calculation of collection area. R_0 is the radius to the point of zero magnetic field in the median plane.

[14] H. J. D. Cole, Proc. Cambridge Phil. Soc. **47**, 196 (1951); and E. Bauler, *ibid.* **47**, 777 (1951).

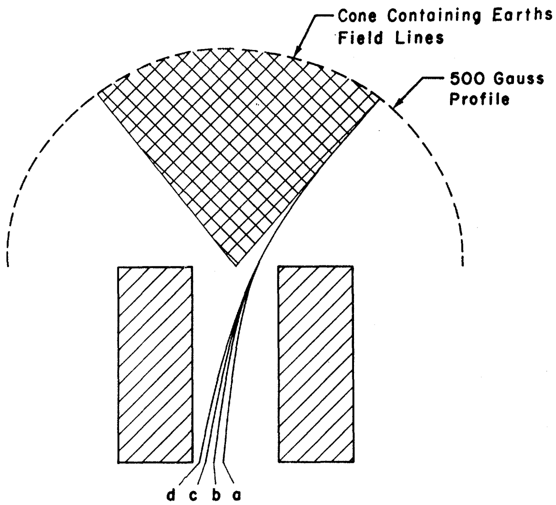

FIG. 4. "Worst case" trajectories for monopoles of various masses. The 500-G profile and the conical cap containing the earth's field lines are explicitly illustrated in relation to the solenoid. The trajectories are for monopoles with mass (a) 2.4 BeV/c^2, (b) 10 BeV/c^2, (c) 50 BeV/c^2, (d) 500 BeV/c^2.

flux with the magnet on, evaluated at the median plane.

$$\Phi_{\text{missing}}=\Phi_{\text{earth}}-[\Phi_{\text{earth}}+\Phi_{\text{magnet}}] = -\Phi_{\text{magnet}}.$$

If R_0 is sufficiently large, we can approximate the solenoid field by a r^{-3} dipole field for $r>R_0$.

$$\Phi_{\text{missing}}=\int B_m dA=\int_{R_0}^{\infty} B_e\left(\frac{R_0}{r}\right)^3 2\pi r dr=2\pi R_0^2 B_e,$$

where B_e is the magnitude of the earth's field and B_m is the field of the magnet. The total geomagnetic flux collected is then $(3\pi R_0^2)B_e$ and the effective area of collection is seen to be $3\pi R_0^2$. Experimentally, we measured $R_0=13$ m so that the total area is calculated to be 1600 m^2.

When the field exceeds about 500 G, the monopole gains more energy from the field than it loses by collision and begins to accelerate. The 500-G profile of our magnet is indicated in Fig. 4. Since we know the total flux of geomagnetic field lines collected, we can use the conservation of flux to calculate the area of the 500-G profile through which the earth's field lines pass. The boundary of this cap-like surface, as indicated in the figure, forms a cone of half-angle 41° with the center of the core. The monopoles appear to accelerate from rest as they emerge from some point within this area of the 500-G profile. By integrating the equations of motion from these points, we determine the trajectories, momenta, and energies. These will be considered for various choices of mass and magnetic charge later; for now we simply note that a 10-BeV/c^2 singly charged monopole will have 36 BeV of kinetic energy and a range of 4.5 g/cm^2 when it reaches the detection apparatus.

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 about a megawatt of power and giving a total of 1.92×10^6 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 1.3×10^9 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.[15] 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[16] 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.×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.×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.

[15] For a review, see F. Brooks, Progr. Nucl. Phys. **5**, 252 (1956).
[16] K. Greisen, *Progress in Cosmic-Ray Physics* (North-Holland Publishing Company, Amsterdam, 1956), Vol. III, p. 60.

TABLE I. Canonical masses.

	No quarks	With quarks
$eg/\hbar c=n/2$ (Dirac)	2.4 BeV/c^2	21.6 BeV/c^2
$eg/\hbar c=n$ (Schwinger)	9.6 BeV/c^2	86.4 BeV/c^2

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.×17 in. and was placed about 10 in. below the bottom of the magnet. Our chamber had four gaps with a $\frac{3}{8}$-in. spacing. The plates were 0.020-in. aluminum sheet (total thickness = 0.685 g/cm^2) 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,[14] 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.×3-in. strips of 400-μ (0.15-g/cm^2) 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 anticoincidence 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/c^2 would be detected if produced.

We noted earlier the Dirac quantization condition, $eg/\hbar c=\frac{1}{2}n$, 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^2 so the higher values of n result in a loss of range. Our detection apparatus is 1.5 g/cm^2 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 $eg/\hbar c=$ integer, or equivalently that Dirac's quantum number n must be even.[17] 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

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

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 overexposures. 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 m^2, we can report no monopoles in a total area-time integral of $AT=6.89\times10^{13}$ cm^2 sec. Thus, we can place an upper limit for the flux of north monopoles in the atmosphere of $R\lesssim3.34\times10^{-14}$ cm^{-2} 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 $R_d\lesssim5.32\times10^{-15}$ cm^{-2} sec^{-1} 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[18]

$$N(E\geqslant E_0)=1.4E_0^{-1.67}\ \text{nucleons/cm}^2\ \text{sr sec},$$

where E_0 is expressed in BeV/c^2. 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 6.1×10^{14} $E^{-1.67}$. Each of these nucleons will interact with a total cross section of about 30×10^{-27} 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 attentuation length to the mean free path of cosmic-ray nucleons. Using measured values for these,[19] we find an improvement factor of about 1.4, so the total number of nucleon-nucleon interactions with energy greater than E is about 8.5×10^{14} $E^{-1.67}$. 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:

$$\text{monopole flux/nucleon flux}=\sigma_{\text{monopole}}/(30\times10^{-27}\ \text{cm}^2),$$
$$\sigma\lesssim8.1\times10^{-41}\ E_{\text{th}}^{1.67}\ \text{cm}^2,$$

where E_{th} is the threshold energy for production of a monopole pair by nucleon-nucleon collision. From elementary kinematics, $E_{\text{th}}=[2(1+M/m)^2-1]mc^2$, 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 $g^2/\hbar c=\frac{1}{4}(137)$.

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

[18] Y. Pal (private communication).

[19] A very useful summary of the characteristics of the interactions of cosmic-ray primary nucleons with the atmosphere is contained in Y. Pal and B. Peters, Kgl. Danske Videnskab. Skelskab, Mat. Fys. Medd. **33**, No. 15 (1964).

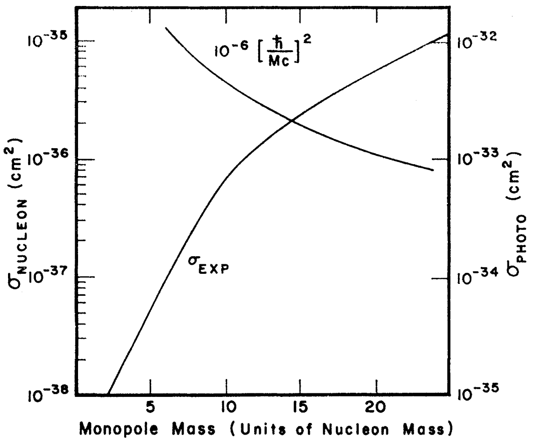

FIG. 5. Plot of experimental cross-section limit and conservative theoretical estimate as a function of monopole mass. The curves are seen to intersect at about 15 nucleon masses.

polarization. We shall take $g^2/\hbar c=1$. The other vertex would be described by the usual electromagnetic strength α. We would then guess that the cross section would be reduced from a strong interaction cross section by a factor of α. Since many competing channels are open we can expect that the cross sections will be considerably reduced from any estimate in the spirit of perturbation theory. We might take as a basic cross section the square of the Compton wavelength of the particle. Such an estimate implicitly recognizes the effects of radiation damping. Finally, our guess would indicate cross sections for a monopole of mass M on the order of $\alpha(\hbar/Mc)^2$. With this guess in mind, we arbitrarily choose a cross section of 10^{-6} $(\hbar/Mc)^2$ as the criterion for a very conservative comparison with experimental cross sections to estimate limits on the monopole mass. This is also plotted in Fig. 5 and is seen to intercept the experimental curve at a monopole mass of about 15 BeV/c^2.

Photoproduction seems likely to be most amenable to an eventual theoretical understanding, so it is desirable to estimate photoproduction cross sections. This we can do by noting that the primary cosmic rays produce π^0 mesons which decay into high-energy γ rays. The charged π mesons decay into μ mesons, and by studying the μ spectra, we can deduce that the charged-pion spectrum has the same energy dependence as the nucleon spectra, but the intensity is reduced by a factor of 100. From elementary symmetry considerations on the ratio of charged to neutral pions, we conclude that the neutral-pion spectra are reduced by a factor of 200 from the nucleon spectra. The γ-ray decay products retain about 80% of the π^0 energy, so they suffer an additional reduction factor of $(0.8)^{2.67}$, or about 0.55. The pair-production length for such γ rays is about 9/7 times the radiation length or about 51 g/cm^2, which should be compared with a nuclear mean free path of 85 g/cm^2. Including some contribution from cascading γ rays, we estimate an over-all production efficiency of 0.5 relative to nucleons. When we combine all these factors, it seems reasonable to estimate an upper limit on photoproduction cross sections about 10^3 times larger than the nucleon cross section. A photoproduction scale is included in Fig. 5.

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, independant 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[12] by a factor of 7000, and smaller than the rate estimated by Goto *et al.*[13] by a factor of about 20. In an accelerator experiment, Purcell *et al.*[9] 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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Differential Cross Sections for $\pi^{\pm}p$ Elastic Scattering in the Momentum Range 875–1579 MeV/c

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Measurements have been made of the differential cross sections for π^+p and π^-p elastic scattering at incident beam momenta in the range 875 to 1579 MeV/c. Two arrays of scintillation counters were used to detect pions scattered from a liquid-hydrogen target in coincidence with recoiling protons. In each of the 25 angular distributions, data were obtained at 18 center-of-mass angles varying from $\cos\theta^*=-0.97$ to $\cos\theta^*=0.75$. The differential cross sections have been expressed as series of the form $d\sigma^{\pm}/d\Omega=\sum_n C_n^{\pm}P_n\times(\cos\theta^*)$. The energy dependence of the coefficients $C_n^{\pm}$ suggests that $N^*(1688)$ has $J=\frac{5}{2}$, $I=\frac{1}{2}$, that $N^*(1928)$ has $J=\frac{7}{2}$, $I=\frac{3}{2}$, and that these two resonances have the same parity. The "shoulder" in the π^+p total cross section at about 950 MeV/c probably occurs in a $J=\frac{1}{2}$ wave.

I. INTRODUCTION

In recent years extensive evidence has been obtained for the occurrence of resonant states in the πN system. Some of this evidence is plotted in Fig. 1 which shows the π^-p and π^+p total cross sections in the range 500–2500 MeV/c.[1–17] The figure also indicates the momenta at which differential cross sections and polarization measurements have been made. Obvious features in the π^-p channel are the peaks at 730

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[1] F. Bulos, R. E. Lanou, A. E. Pifer, A. M. Shapiro, M. Widgoff, R. Panvini, A. E. Brenner, C. A. Bordner, M. E. Law, E. E. Ronat, K. Strauch, J. Szymanski, P. Bastien, B. B. Brabson, Y. Eisenberg, B. T. Feld, V. K. Fischer, I. A. Pless, L. Rosenson, R. K. Yamamoto, G. Calvelli, L. Guerriero, G. A. Salandin, A. Tomasin, L. Ventura, C. Voci, and F. Waldner, Phys. Rev. Letters **13**, 558 (1964).

[2] R. W. Kenney, C. B. Chiu, R. D. Eandi, B. J. Moyer, J. A. Poirier, W. B. Richards, R. J. Cence, V. Z. Peterson, and V. J. Stenger, Bull. Am. Phys. Soc. **9**, 409 (1964).

[3] D. E. Damouth, L. W. Jones, and M. L. Perl, Phys. Rev. Letters **11**, 287 (1963).

[4] R. D. Eandi, T. J. Devlin, R. W. Kenney, P. G. McManigal, and B. J. Moyer, Lawrence Radiation Laboratory Report No. UCRL-11501 (unpublished).

[5] R. D. Eandi, T. J. Devlin, R. W. Kenney, P. G. McManigal, and B. J. Moyer, Phys. Rev. **136**, B536 (1964).

[6] J. A. Helland, T. J. Devlin, D. E. Hagge, M. J. Longo, B. J. Moyer, and C. D. Wood, Phys. Rev. **134**, B1062 (1964).

[7] J. A. Helland, C. D. Wood, T. J. Devlin, D. E. Hagge, M. J. Longo, B. J. Moyer, and V. Perez-Mendez, Phys. Rev. **134**, B1079 (1964).

[8] P. M. Ogden, Lawrence Radiation Laboratory Report No. UCRL-11180 (unpublished).

[9] E. H. Bellamy, T. F. Buckley, W. Busza, D. G. Davies, B. G. Duff, F. F. Heymann, P. V. March, C. C. Nimmon, A. Stefanini, J. A. Strong, R. N. F. Walker, and D. T. Walton, Proc. Roy. Soc. (London) **A289**, 509 (1966).

[10] A. S. Carroll, A. B. Clegg, I. F. Corbett, C. J. S. Damerell, N. Middlemas, D. Newton, T. W. Quirk, and W. S. C. Williams, Proc. Roy. Soc. (London) **A289**, 513 (1966).

[11] P. Bareyre, Proc. Roy. Soc. (London) **A289**, 463 (1966).

[12] P. Bareyre, C. Bricman, M. J. Longo, G. Valladas, G. Villet, G. Bizard, J. Duchon, J. M. Fontaine, J. P. Patry, J. Seguinot, and J. Yonnet, Phys. Rev. Letters **14**, 878 (1965).

[13] T. J. Devlin, J. Solomon, and G. Bertsch, Phys. Rev. Letters **14**, 1031 (1965).

[14] J. C. Brisson, J. F. Detoeuf, P. Falk-Vairant, L. van Rossum, G. Valladas, and L. C. L. Yuan, Phys. Rev. Letters **3**, 561 (1959).

[15] T. J. Devlin, B. J. Moyer, and V. Perez-Mendez, Phys. Rev. **125**, 690 (1962).

[16] A. N. Diddens, E. W. Jenkins, T. F. Kycia, and K. F. Riley, Phys. Rev. Letters **10**, 262 (1963).

[17] A. Stirling *et al.* (to be published). For a tabulation of the data see B. Amblard, P. Borgeaud, Y. Ducros, P. Falk-Vairant, O. Guisan, W. Laskar, P. Sonderegger, A. Stirling, M. Yvert, A. Tran Ha, and S. D. Warshaw, Phys. Letters **10**, 138 (1964).