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Sea-Level Search for Cosmic Magnetic Monopoles

R.L. Fleischer, H.R. Hart, Jr., G.E. Nichols, and P.B. Price*
General Electric Research and Development Center, Schenectady, New York 12301
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On the hypothesis that the highest-energy cosmic rays consist at least in part of magnetic monopoles, heavily ionizing particles have been sought at ground level using an 18-m^2 detector array exposed for 630 days. The observable flux of Dirac monopoles at ground level is less than $1.5\times10^{-9}/m^2$ sec sr with 95% confidence. Monopoles are not the dominant cause of air showers having energies up to 3.0×10^{16} eV.

INTRODUCTION

The forty years since Dirac suggested the possibility of the existence of free magnetic charges in nature[1] have been noteworthy both for the many searches for magnetic monopoles and for the complete lack of evidence that such particles do exist.[2,3] Three possible explanations of why no free monopoles have been observed are (1) they do not exist, (2) they are so infrequent that the existing searches were not sufficiently intense, and (3) they occur only with combinations of mass and pole strength (magnetic charge) that could not have been observed in the previous searches. Here we recognize possibility (3) and present results which cover the previously unassessed mass–magnetic-charge region.

We wish to assess the possibility suggested by Porter[4] that the high-energy cosmic rays ($>10^{16}$ eV) consist of magnetic monopoles. Porter was led to his suggestion as a way out of the problem of explaining the origin of these high-energy events. At the energies involved, cosmic-ray protons are not trapped within our galaxy and hence would need either to be accelerated in great abundance by a single-step process within the galaxy or to originate outside the galaxy, both possibilities being astrophysically difficult to accept. In contrast, if monopoles exist, it is easy to show[5] that they could be accelerated within the galaxy to what would otherwise be regarded as mysteriously high energies.

The mass–magnetic-charge domain that we have previously explored[3] and the domain of the present experiment are indicated in Fig. 1. Charge $\hbar c/2e$ monopoles, which we refer to as *Dirac monopoles*, are the minimum allowed by Dirac's theory, while multiples of 2, 4, and 8 are predicted by more recent theories of Schwinger.[6] If quarks exist, multiples of 3 and 12 become possible. From Fig. 1 we see that a gap exists. Monopoles having twice the Dirac charge should have been seen in natural minerals such as obsidian or mica,[8] but their ionization rate places them close enough to the threshold of detection[9] that further assessment of charge-2 monopoles is desirable. However, Dirac monopoles of mass exceeding $100m_p$ (m_p = proton mass) would have been recognized in the two previous experiments[10,11] only if they were an abundant component of the shower-producing cosmic radiation. The first of these experiments is the Tyan'-Shan' high-altitude extensive air shower array,[10] which set a limit (95% confidence) of $2\times10^{-12}/cm^2$ sec sr in the energy range 3×10^{13} to 10^{16} eV.

The only other experiments besides Ref. 10 that could have detected massive (mass $>100m_p$) charge-2 cosmic monopoles with certainty are the high altitude balloon exposures of large-area detectors that have been flown during the last few years. A recent summary of the results[11] shows a cumulative (area)×(time) factor of 7.6×10^6 m^2 sec. Since a fast moving monopole of charge 2 would have the ionizing effect of a relativistic electrically-charged particle of atomic number 137 (Ref. 12), it would produce a totally unique track.

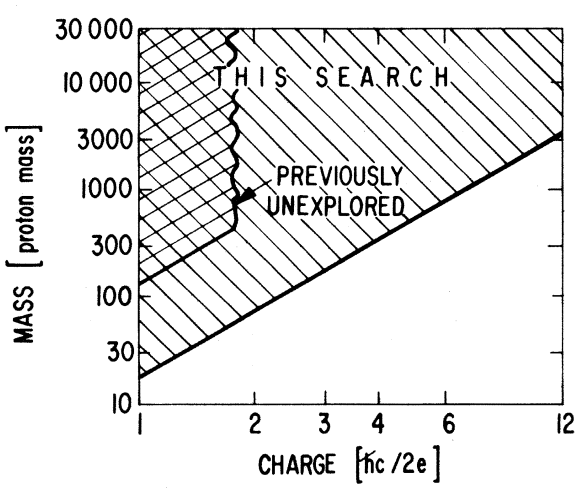

FIG. 1. Mass–magnetic-charge domains of our previous work and of this study (adapted from Fig. 5 of Ref. 3 using calculations outlined in Ref. 7). Charge 1 is Dirac's original minimum value.

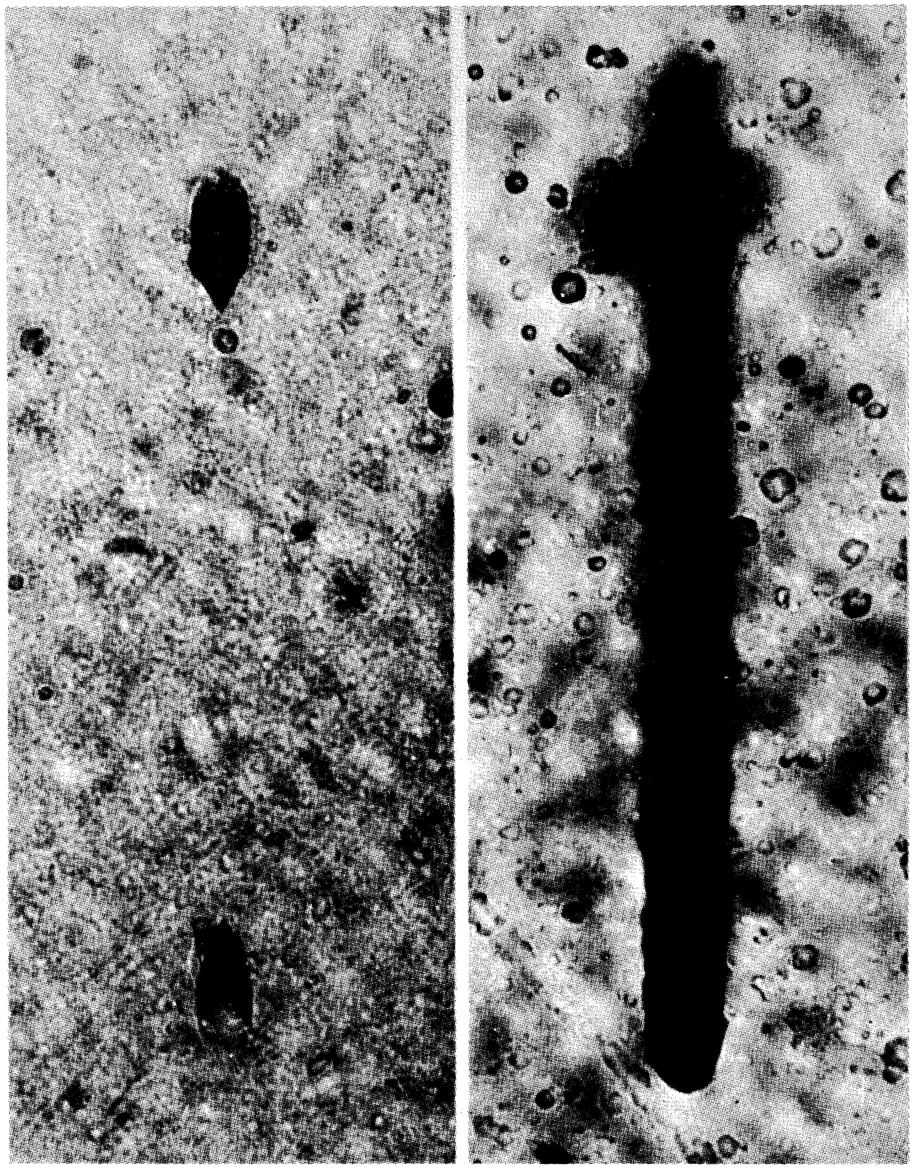

FIG. 2. Tracks in two different plastic sheets left by a single particle whose ionization is equivalent to that expected of a Dirac monopole. Left: track in Lexan polycarbonate; right: track in cellulose nitrate. The track diameters are approximately 17 μ and 23 μ, respectively. The two sheets in which the tracks appear were part of a stack flown in a balloon at an altitude of 130 000 feet to observe heavy cosmic-ray particles (Ref. 13).

Because no such particles were seen, we can use the (area)×(time) factor to set an upper limit on the flux of monopoles with charge $\geqslant 2$. Dirac monopoles, however, have the effect of charge-68.5 nuclei, closely approximated by a particle whose track is shown in Fig. 2. Although the track-forming particle could, in principle, have been a monopole, it is almost surely a cosmic ray of charge close to 68 or 69. From Ref. 11 we know the flux of such particles near the top of the atmosphere and therefore can again construct an upper limit to the monopole flux. Table I represents the limits from the balloon flights, along with the highest energy in the cosmic-ray energy spectrum that we have thereby checked for monopoles. Unfortunately, we note that the interesting region above 10^{16} eV has not been attained. Consequently, an experiment with higher collecting power is required and one positioned such that the background of cosmic rays of charge close to 68.5 is absent.

The logical place for such an experiment is beneath the earth's atmosphere, where two conditions are met. Firstly, the monopoles of interesting mass ($>20m_p$) and charge ($\hbar c/2e$ and $\hbar c/e$) should

TABLE I. Limits on monopole flux from cosmic-ray experiments near the top of the atmosphere.

Magnetic charge	Flux (95% confidence) $[(\mathrm{m}^2\,\mathrm{sec\,sr})^{-1}]$	Maximum cosmic-ray energy tested (eV)
$\hbar c/2e$	$<7.1\times10^{-7}$	2×10^{15}
$\geq\hbar c/e$	$<1.2\times10^{-7}$	5×10^{15}

TABLE II. Limits on monopole flux at sea level.

Magnetic charge	Flux (95% confidence) $[(\mathrm{m}^2\,\mathrm{sec\,sr})^{-1}]$	Maximum cosmic-ray energy tested (eV)
$\hbar c/2e$	$<1.52\times10^{-9}$	3×10^{16}
$\geq\hbar c/e$	$<1.25\times10^{-9}$	4×10^{16}

readily penetrate. At sea level, this is true if they are incident at energies above $\sim5\times10^{13}$ eV. Secondly since the interaction mean free path in air for nuclei of charge ~68 is ~7.8 g/cm^2, the flux of this unwanted background at sea level is $\sim10^{-50}$/m^2 Myr sr, low enough to be ignored with some safety. With these considerations in mind we have exposed a large-area detector array at sea level.

EXPERIMENTAL

The array consisted of six 1.22-m by 2.44-m panels each covered with one thickness of 254-μ Lexan polycarbonate sheet and either one or two 76-μ thicknesses. Panels A, B, and C were exposed in a field adjacent to the Research Laboratory's No. 3 and No. 4 parking lots for approximately $1\frac{1}{2}$ years, a total of 4.13×10^{12} cm^2 sec. During that time the detectors were protected from ultraviolet effects[14] and solar heating by a canopy composed of polyethylene supported by chicken wire and covered with aluminized Mylar having the aluminized side down. During the next three months, these same panels were exposed in air-conditioned quarters inside the Research Laboratory under a roof consisting of ≈13 g/cm^2 air equivalent. Panels D, E, and F were exposed inside throughout the experiment. The total exposure of all six panels amounted to 8.76×10^{12} cm^2 sec.

The detectors of thickness 254 μ were cut into ~30×40-cm sheets and were then developed for rapid scanning using an etch composed of 1 part 6.25N NaOH to 1 part ethanol by volume,[15] adjusting the time so that the average thickness was reduced to 60 μ. Sheets were scanned using the Ozalid process for locating etched holes which cross the detector sheet.[16] Because a track must penetrate the detector to be observed, there is an etching efficiency η to the processing that depends on the half-angle θ of the etched, cone-shaped track, and on the fractional reduction in thickness δ. η can be shown to be given by $1-[(\sin\theta)/\delta]^2$. From our etching procedure and the calibrations given in Ref. 15, we infer that for Dirac monopoles, $\eta=0.809$, and for monopoles of charge ≥2, η is ≥0.986. In addition the Ozalid processing is such that the border of each sheet is not usefully scanned, and for this reason there was a 10.5% loss of area. Finally, during the exposure inside the laboratory, there is a 4% loss of collecting area because of a partial overlap of the solid angles viewed by the panels during part of the exposure.

RESULTS

No particle tracks of any sort were found. Because of the extensive etching, approximately 30 flaws/m^2 etched through the sheets; these were inspected in each case by at least two observers. The flaws were distinctive and could be readily rejected after inspection at 60× in a stereo microscope. Any questionable cases were checked using controlled etching of the portions of the 76-μ sheets that were adjacent to possible tracks. No matching tracks were found, and hence the possible tracks were not monopoles.

DISCUSSION AND CONCLUSIONS

The lack of observed particles can be used to set limits on the flux of heavily ionizing particles at sea level, limits that appear in Table II. We have lowered the limits on the flux of Dirac poles in the cosmic rays by a factor of more than 15, but because of the steepness of the energy spectrum, the energy to which we have "tested" the cosmic rays for massive monopoles is increased by only 3 or 4 times relative to extensive air shower arrays.[10] A major consideration, however, is that the limit has now been pushed above the 10^{16}-eV mark. If all cosmic rays above 10^{16} eV were massive monopoles, we would have seen ~5000 Dirac poles or ~6000 poles if the magnetic charge were $\geq\hbar c/e$.

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*Now at Department of Physics, University of California, Berkeley, Calif.
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Direct Production of Electron Pairs in Nuclear Emulsion by 13.75-BeV Electrons*

Arthur S. Cary,† Walter H. Barkas,‡ and Edward L. Hart§
University of California at Riverside, Riverside, California 92502
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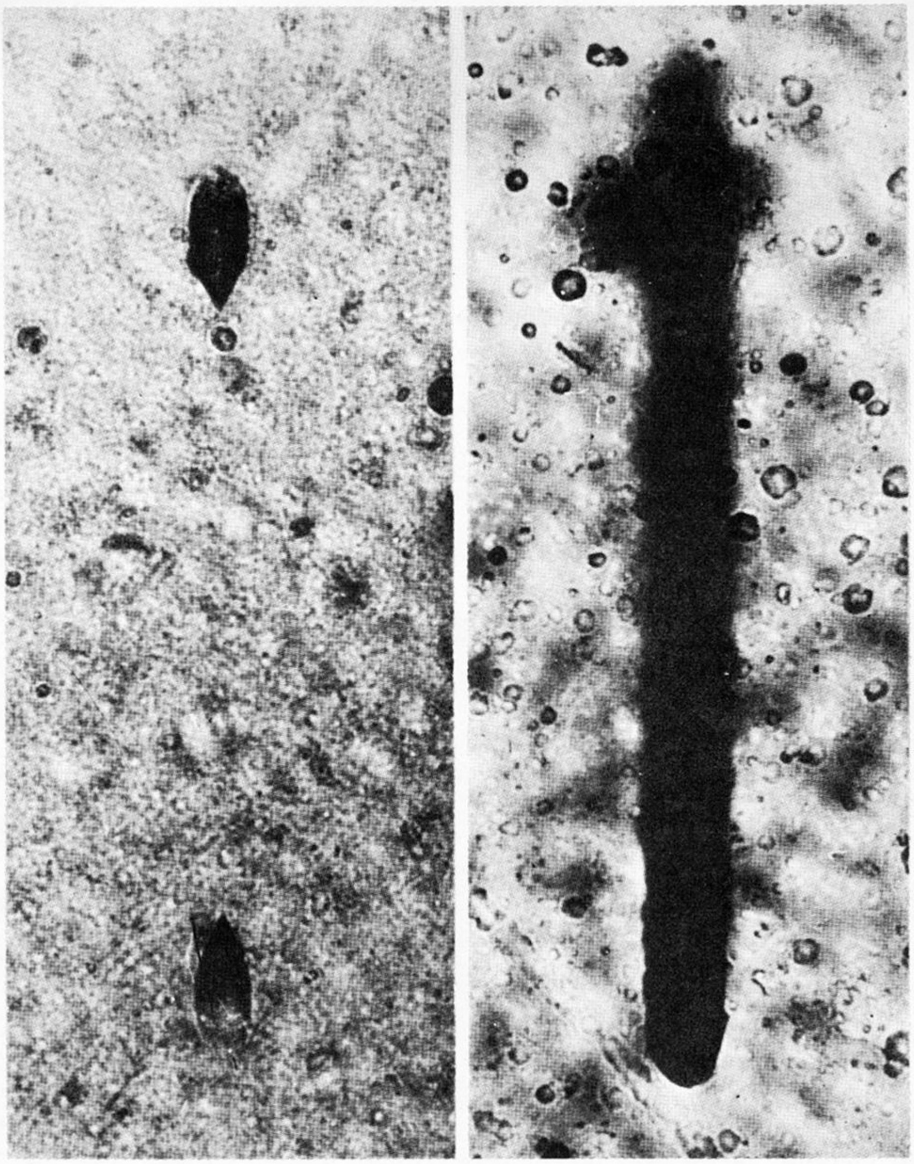
A measurement has been made of the total cross section for direct production of electron pairs by 13.75-BeV electrons in nuclear emulsion. The result, $(4.03 \pm 0.36) \times 10^{-25}$ cm^2, is in good agreement with quantum electrodynamics.

Many experiments[1] on the direct production of electron pairs in the field of nucleus, $e^- + (A) \rightarrow e^- + e^+ + e^- + (A)$, have been carried out in nuclear emulsion. These experiments have used electrons and positrons produced in cosmic-ray showers as the parent particle. The observed large cross sections have led to uncertainty as to whether the process may not have a cross section as much as a factor of five times the value predicted by quantum electrodynamics (QED). Previous works have been hampered in their efforts to resolve this difficulty by the uncertainty in the energy of the primary cosmic-ray electron, unsatisfactory approximation methods for correcting for pseudotridents (false direct pairs) produced by bremsstrahlung radiation, and poor statistics.

Cloud-chamber[2] and counter[3] observations of the trident process at low energies, below 15 MeV, have been in general agreement with theory. Recently, Grossetête[4] *et al.* have measured the differential cross section using counters and a primary electron beam of 500 MeV from the Stanford accelerator. Their results are in good agreement with the calculations made for the trident process, using the Feynman-Dyson method, by Murota, Ueda, and Tanaka.[5]

Expressions for the total cross section for tridents have been discussed extensively in several articles.[6] At very high primary electron energy, the expression for the cross section obtained by Racah, and Murota, Ueda, and Tanaka, and the Bhabha equation, modified by Block *et al.*,[7] are in basic agreement. The expression for the total cross section, as developed by Block and King,[8] is used in this paper when comparing theoretical and experimental results.

Twenty-four Ilford G5 emulsion plates of size $(2.5 \times 13\ \text{cm}^2) \times (200\ \mu)$ were exposed to a 13.75-BeV electron beam at SLAC. The beam contained about 2.5% pion contamination. In an along-the-track scan of the entering primary particles, each beam track was followed a distance of 1 cm into the emulsion. A total scanned track length of 4951 cm yielded 984 apparent tridents. The general characteristics of the apparent trident events were a sudden increase (three times) in grain density of the primary electron, and the subsequent appearance of three minimum-ionizing tracks pro-



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