Evidence for Detection of a Moving Magnetic Monopole

P. B. Price* and E. K. Shirk*
Physics Department, University of California, Berkeley, California 94720

and

W. Z. Osborne† and L. S. Pinsky‡
Physics Department, University of Houston, Houston, Texas 77004

(Received 4 August 1975)

A very heavy particle passed through a balloon-borne stack of Cherenkov film, emulsion, and Lexan sheets. In 33 Lexan sheets it produced tracks expected of either a nucleus with $125 \lesssim Z \lesssim 137$ and $\beta \lesssim 0.92$ or a magnetic monopole with $g = 137e$. Its track structure in emulsion indicated it was moving downward with $\beta = 0.5^{+0.1}_{-0.05}$ and was either a nucleus with $Z \approx 80$ or a monopole with $g = 137e$. These facts strongly favor identification of the particle as a magnetic monopole of strength $g = 137e$ and mass $> 200 m_p$.

In the last of our series of balloon flights to study ultraheavy cosmic rays ($Z \geqslant 60$) at low geomagnetic cutoff, the multilayer stack, 20 m^2 in area, shown in Fig. 1, was exposed for 2.6 days at an atmospheric depth of ~3 g/cm^2 near Sioux City, Iowa, on 18 September 1973. Here we present our analysis of one event that differs from any seen in previous balloon flights[1] or in the Skylab ultraheavy-cosmic-ray experiment.[2]

The event was found in a stereomicroscopic scan of the emulsion layer and was recorded as having $Z \approx 80$ and $\beta = 0.5^{+0.1}_{-0.05}$ on the basis of track-structure measurement made with an eyepiece reticle and a microscope. The estimates of Z and β guide us in choosing the optimum times for chemically etching the portions of the Lexan sheets along a particular event. Cone-length measurements in the Lexan then yield much more precise estimates of charge and velocity. The fast-film Cherenkov detectors furnish independent velocity estimates for $Z \gtrsim 70$ and $\beta > 0.68$. Figure 1 summarizes the information derived from each type of detector. Only the interpretation of the particle as a magnetic monopole with $g = 137e$ and $\beta \approx 0.5$ is consistent with all the available information.

Figure 2 shows the data from the Lexan detector. The triangles represent data from a 20-h etch and the solid circles for a 30-h etch in a separate tank.[3] All measurements were made by two observers. The points reproduce to within ±0.05 μm/h.

In previous analyses[2,3] of ultraheavy cosmic rays we have found the etch rate v_T depends on ionization rate approximately as

$$v_T = \text{const}(Z^*/\beta)^4, \tag{1}$$

where Z^* is the effective charge. The scale at the bottom of Fig. 2 is the estimated charge assignment if $\beta \approx 1$. The best fit to the data is given by a zero slope (rate of change of etch rate with depth), corresponding to a hypothetical charged particle with $Z \approx 137$ and $\beta \approx 1$. For the maximum slope, S_{max}, consistent with the data (84% confidence), the charge is $Z \approx 125$ and $\beta \approx 0.92$. In no previous flight with Lexan detectors has an event been found with $Z \gtrsim 96$. This is reasonable because ${}^{247}_{96}\text{Cm}$ is the heaviest known nuclide with a half-life (in its rest frame) greater than 10^6 yr.

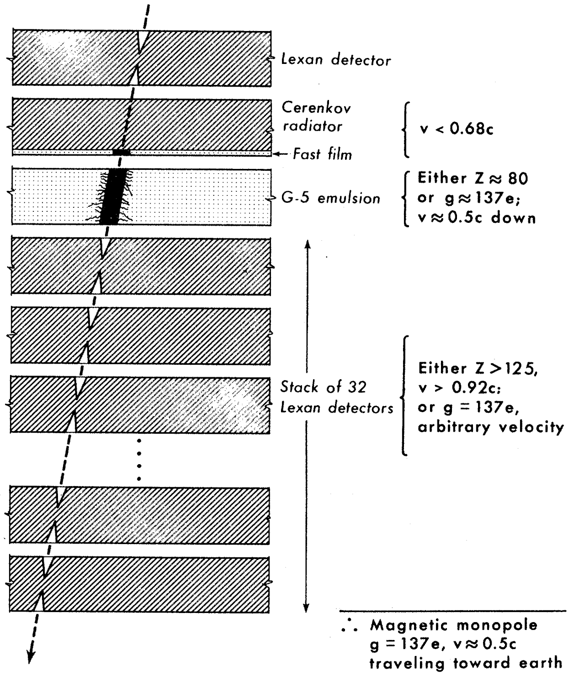

FIG. 1. Stack of balloon-borne detectors.

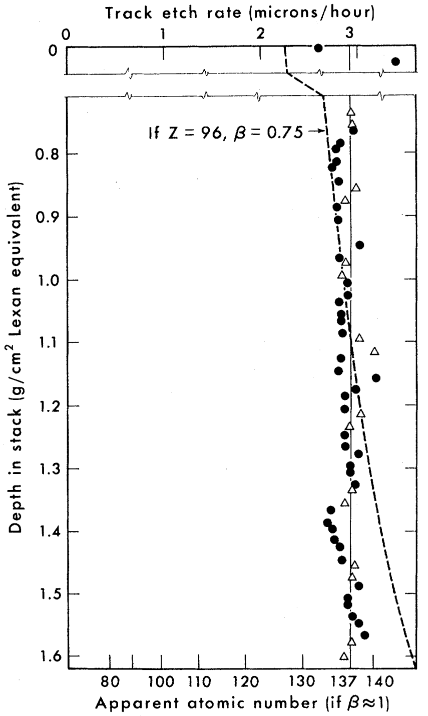

FIG. 2. Etch-rate data. See text. Emulsion data rule out dashed curve or any fit to a nucleus with $\beta > 0.5^{+0.1}_{-0.05}$.

The dashed curve in Fig. 2 shows the best fit to the data for a nucleus of $Z = 96$; its velocity must be $\sim 0.75c$; its slope is ~ 18 times $S_{\max}$. The ionization rate of a magnetic monopole of strength g is given[5-7] by replacing Z^*e by $g\beta$, so that for a monopole Eq. (1) must be replaced by

$$v_T = \text{const}(g/e)^4. \qquad (2)$$

The solid line in Fig. 2 is consistent with a monopole of strength twice the minimum strength $g_0 = \hbar c/2e = (137/2)e$ of Dirac's hypothetical magnetic monopole.[4] Thus, the etch-rate data admit of only two alternatives:

(1) The particle was a nucleus with $Z \gtrsim 125$, $\beta \gtrsim 0.92$.

(2) The particle was a monopole with $g = 137e$ and any velocity sufficient to penetrate the 1.6-g/cm² stack.

The data from the nuclear emulsion and Cherenkov film enable us to reject the first alternative. One of us[8] has extended the track model of Kobetich and Katz[9] and their electron-energy-deposition algorithm[10] to obtain detailed predictions of ion-track structure from the track core out to the maximum lateral extent of the δ rays for wide ranges of Z and β. Subsequently, we[11] modified these calculations to include the Mott cross section[12] rather than the Rutherford cross section. These results are in agreement with our accumulated experience from almost 100 ultraheavy-cosmic-ray events, and allow us to predict monopole-track structure by the substitution $Z^* = 137\beta$. Katz and Butts[7] predicted monopole-track core widths based on the Rutherford cross section, but did not consider structure outside of the core region. A useful way to display our results is to plot R_1, the radius at which the probability of grain development is 0.4 versus R_2, the radius at which the probability of grain development is 0.001. R_1 corresponds to the core radius and R_2 to the limit of visual perception of a signal above background. Figure 3 contains results for $Z = 30$, 70, and 110, and for a monopole with $g = 137e$.

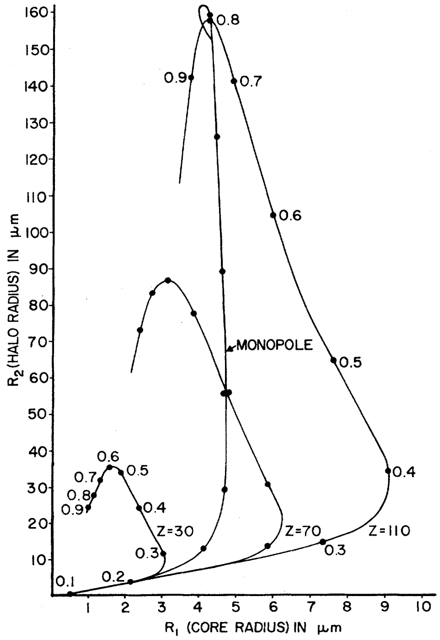

FIG. 3. Method of estimating charge and velocity from track structure in emulsion. See text. Numbers along curves give $\beta = v/c$.

Because of the steepness of the track, R_1 could not be measured accurately but was ~ 6 μm. The observed R_2 was 55 μm, consistent with a monopole with $\beta \approx 0.5$, but totally inconsistent with the R_2 (130 μm) expected for a nucleus with $Z > 125$ and $\beta > 0.92$. Observations of Fe tracks that stopped in the Lexan showed that the emulsion had normal sensitivity.

Our measurements show that, among the identifiable individual δ rays, downward-directed tracks outnumber upward-directed tracks by at

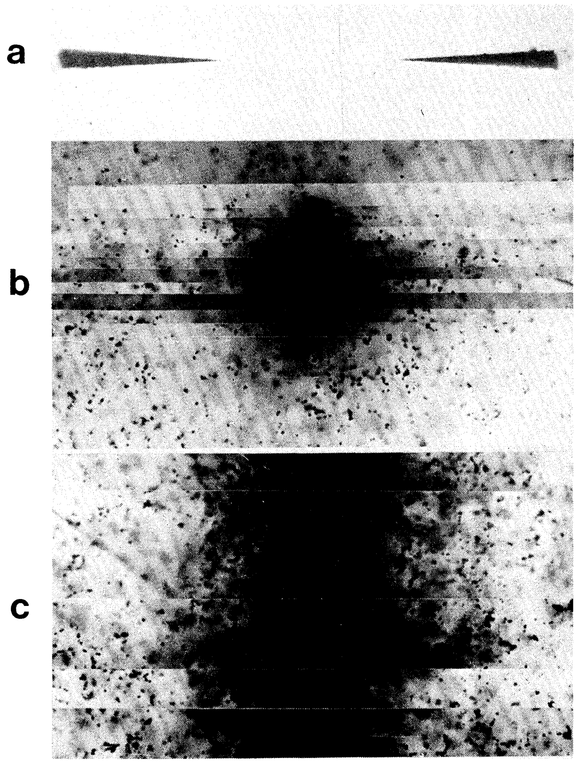

FIG. 4. Photomicrographs of the monopole track in (a) a Lexan sheet (epoxied, sliced, and viewed edge-on), and (b) G-5 emulsion (viewed nearly vertically). In (c), note the greater lateral extent of δ rays from a nucleus with $Z \approx 92$ and $\beta \approx 0.6$.

least 5 to 1. We conclude that the monopole was moving downward.

Figure 4 shows photomicrographs of the monopole track in one sheet of Lexan and in the emulsion, together with a photomicrograph of the track of the heaviest nucleus found in the flight. From its R_1 (~ 5 μm) and R_2 (110 μm) in emulsion it was estimated to have $Z \approx 95$, $\beta \approx 0.65$. It came to rest in the Lexan stack. Measurements of its etch pits showed that $Z \approx 92$ and $\beta \approx 0.6$ at the emulsion.

A fast-film Cherenkov detector consisting of a thin plastic Cherenkov radiator, coated with Eastman Kodak 2485 film, records an elliptical image at the trajectory of a charged particle of $Z \gtrsim 70$ and $\beta > \beta_{\text{crit}} \equiv n^{-1}$, where n is the refractive index of the radiator.[3,13] The intensity of the image is proportional to $(Ze)^2(1 - n^{-2}\beta^{-2})$ for a charged particle and to $g^2(n^2 - \beta^{-2})$ for a monopole. We have examined the appropriate region of our fast-film Cherenkov detector and have found a small ionization spot but no elliptical Cherenkov image. Eight other regions traversed by high-energy, high-Z nuclei during this flight showed normal Cherenkov images. We conclude that the particle in question had a velocity $\beta \lesssim 0.68$ in the Cherenkov radiator.

Independent of all details of calibration of response of the Lexan and the emulsion, the essence of our observations is that we have found a particle of velocity $\sim 0.5c$ that ionized heavily and at a constant rate as it slowed down through 1.6 g/cm^2 of matter. This constancy of ionization rate was first shown by Dirac[4] to be a property of magnetic monopoles. A particle with only electric charge and velocity $0.5c$ would have to have an enormous ratio of mass to charge to fit the data ($>10^4$ proton masses and $Z \approx 70$). Neither a Lee-Wick abnormal nucleus[14] nor a small, charged black hole[15] is consistent with the evidence.

We conclude that we have detected a magnetic monopole of strength $g = 137e$ and velocity $(0.5^{+0.1}_{-0.05})c$. In order to penetrate the ~ 1-g/cm^2 Lexan stack its energy must exceed 32 GeV, which means that its mass must exceed ~ 200 proton masses. Its existence rules out the existence of free quarks or other fractionally charged particles.

Based on this one event out of numerous balloon flights and one satellite exposure of large detectors of heavily ionizing particles, the flux of monopoles of strength $137e$ near the top of the atmosphere with velocity sufficient to penetrate track detectors is $\sim 10^{-13}$ cm^{-2} sec sr. The apparent conflict between this flux and the negative results obtained in previous monopole searches[16] places strong constraints on the properties of monopoles.

We thank G. Blanford, H. H. Heckman, R. Smith, J. Teague, and W. Wagner for assistance; Clark Goodman, D. Hagge, and D. Kurz for support; and S. Ahlen, L. Alvarez, B. G. Cartwright, G. Tarlé, and L. W. Wilson for discussions.

---

*Work supported by National Aeronautics and Space Administration Grant No. NGR 05-003-376 and U. S. Energy Research and Development Administration Contract No. AT (04-3)-34.

†Work supported by National Aeronautics and Space Administration Grant No. NGR 44-005-041.

[1] M. H. Israel, P. B. Price, and C. J. Waddington, Physics Today 28 (5), 23 (1975); P. H. Fowler, in *Proceedings of the Thirteenth International Conference on Cosmic Rays, Denver, Colorado, 1973* (Univ. of Denver, Denver, Colo., 1973), Vol. 5, p. 3627.

[2] E. K. Shirk and P. B. Price, to be published.

[3] E. K. Shirk, P. B. Price, E. J. Kobetich, W. Z. Osborne, L. S. Pinsky, R. D. Eandi, and R. B. Rushing, Phys. Rev. D 7, 3220 (1973).

[4] P. A. M. Dirac, Proc. Roy. Soc. (London), Ser. A 133, 60 (1931), and Phys. Rev. 74, 817 (1948).

[5] H. J. D. Cole, Proc. Cambridge Philos. Soc. 47, 196 (1951).

[6] E. Bauer, Proc. Cambridge Philos. Soc. 47, 777 (1951).

[7] R. Katz and J. J. Butts, Phys. Rev. 137, B198 (1965).

[8] W. Z. Osborne, unpublished results.

[9] E. J. Kobetich and Robert Katz, Phys. Rev. 170, 405 (1968).

[10] E. J. Kobetich and R. Katz, Nucl. Instrum. Methods 71, 226 (1969).

[11] W. Z. Osborne and J. L. Lacy, to be published.

[12] J. A. Doggett and L. V. Spencer, Phys. Rev. 103, 1597 (1956).

[13] L. S. Pinsky, R. D. Eandi, W. Z. Osborne, and R. B. Rushing, in *Proceedings of the Twelfth International Conference on Cosmic Rays, Hobart, Australia, 1971* (Univ. of Tasmania Press, Hobart, Australia, 1971), Vol. 4, p. 1630.

[14] T. D. Lee and G. C. Wick, Phys. Rev. D 9, 2291 (1974).

[15] S. Ahlen and G. Tarlé, private communication.

[16] For a compilation of searches up to 1971, see P. H. Eberhard, R. R. Ross, L. W. Alvarez, and R. D. Watt, Phys. Rev. D 4, 3260 (1971).

Experimental Signature of Scaling Violation Implied by Field Theories

Wu-Ki Tung*

Enrico Fermi Institute, Department of Physics, University of Chicago, Chicago, Illinois 60637

(Received 18 March 1975)

Renormalizable field theories are found to predict a surprisingly specific pattern of scaling violation in deep inelastic scattering. Comparison with experiments is discussed. The feasibility of distinguishing asymptotically free field theories from conventional field theories is evaluated.

A problem of central importance in particle physics today is to understand the gross scaling behavior of the structure functions in deep inelastic lepton-hadron scattering and to pin down the pattern of violation of strict scaling, if any. Much effort has been spent in studying this problem in the general framework of renormalizable field theories.[1] This raised the exciting possibility of gaining crucial evidence toward answering the long-standing question of *whether renormalizable field theories are viable as the underlying theory for hadron physics*. The bases for this hope are as follows: (i) Strict Bjorken scaling is incompatible with renormalizable field theories (except in the trivial case of free particles)[2]; (ii) techniques have now been developed to extract from these theories[3,4] the expected pattern of scaling violation which can be confronted with experiment.[5]

Assuming the answer to the question posed above turns out to be yes, a second interesting question to ask is: *Can the data further distinguish which class of field theories is the relevant one for hadron physics?* Here I have in mind, in particular, the conventional type (CT) versus the much publicized asymptotically free (AF) field theories.[5]

An evaluation of the prospect for resolving these important issues by forthcoming experiments cannot be made until the expected patterns of scaling violation are systematically analyzed. Here I carry out such an analysis and compare the results obtained for the two types of theories with available data as well as with each other. These studies indicate great promise for gaining insight into the questions raised; they also identify crucial features to be looked for in the next generation of experiments.

For definiteness, throughout this paper we shall be concerned with the well-known structure function νW_2 which we simply denote by $F(x,q^2)$, where $x = q^2/2M\nu$. It is one of the two independent spin-averaged current correlation functions $\langle N|J^\mu(z)J^\nu(0)|N\rangle$, where J^μ is the electromagnetic current operator.[1] The scaling-limit behavior of $F(x,q^2)$ can be studied in renormalizable field theories by the technique of Wilson expansion[1] of the operator product $J^\mu(z)J^\nu(0)$ and the application of the Callan-Symanzik equation to the coefficient functions in this expansion.[3] Contact with experiment is made through the moment integrals

$$\int_0^1 dx\, x^{n-2} F(x,q^2) = M(n,q^2). \qquad (1)$$

Typically, CT theories imply the following high-

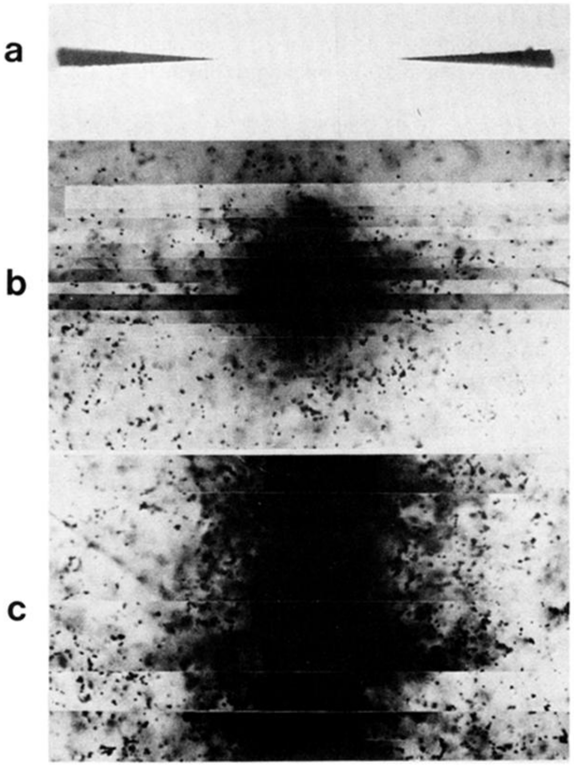

FIG. 4. Photomicrographs of the monopole track in (a) a Lexan sheet (epoxied, sliced, and viewed edge-on), and (b) G-5 emulsion (viewed nearly vertically). In (c), note the greater lateral extent of δ rays from a nucleus with $Z \approx 92$ and $\beta \approx 0.6$.