Probabilities for an Alternative Explanation of the Moving Magnetic Monopole

R. L. Fleischer
General Electric Research and Development Center, Schenectady, New York 12301

and

R. M. Walker
Washington University, St. Louis, Missouri 63130
(Received 18 September 1975)

The cosmic-ray track that has been interpreted as a magnetic monopole may in principle be from a nucleus that underwent nuclear interactions. The *a priori* probability of this latter process is calculated to be $\sim 10^{-13}$ if the particle moved at the reported velocity of $<0.6c$, but rises to $\sim 10^{-3}$ if $0.7c$ is allowed. Among the number of cosmic rays already examined, the total predicted probabilities for observing such an interacting event would have been $<7\times 10^{-13}$ at $<0.6c$ and $\sim 2\%$ at $0.7c$.

A recent analysis[1] of cosmic-ray particles detected in a high-altitude balloon flight describes one unusual cosmic-ray event as being best explained by a magnetic monopole. Because of the profound significance to physics and possibly to technology of the existence of free magnetic charges, it is important that the chances of an alternative explanation be assessed. The search for an alternative description is also spurred by two discrepancies. The major inconsistency is experimental: The sequence of studies of heavily ionizing particles in the cosmic radiation[2] that led to the finding of the proposed monopole utilized a collecting power that is only 10^{-6} of that of some of the previous monopole searches.[3] The second inconsistency arises from a calculation of the lifetime of galactic magnetic fields, which moving magnetic poles would erase. The inferred flux from Ref. 1 and a straightforward calculation by Parker[4] yield a lifetime of less than 10 000 yr. A special mechanism would be required to continuously generate the magnetic fields throughout the galaxy on so short a time scale. However, since only one particle has been observed, flux arguments are somewhat lacking in force; the possibility always remains that the event in question was a million-to-one shot.

The case for the particle being a monopole is its nearly constant ionization level as observed in the polycarbonate detectors and its low velocity $(0.5^{+0.1}_{-0.05})c$ inferred from a nuclear emulsion. The velocity measurement is consistent with the absence of Čerenkov light in a Čerenkov film that would have seen such light if the velocity significantly exceeded $0.68c$. Any single atomic nucleus at the quoted velocity would change its ionization in a clearly visible manner in crossing the polycarbonate stack.

We consider two classes of alternative explanations: (a) the feasibility that the interferences are drawn in fact from experimental artifacts and (b) the possibility that other known physical processes, not considered by Price *et al.*, provide a reasonable explanation of the data.

For discussion we accept that the particle was moving downward with the velocity of $\leq 0.70c$ that is required by the Čerenkov detector. It is well known that environmental effects such as exposure to light, storage at room temperature, and exposure to reactive gas species can greatly influence the rate of track etching in Lexan.[5] Chemical differences between Lexan sheets or differences in the conditions used to etch them could similarly affect the etching rates. The 30% difference in track etch rates between the two data points reported for the top Lexan sheet, which during the operation of the flight and subsequent disassembly was treated differently than the others, suggests the possibility that such effects may have been present. Although Price *et al.* state that all the other Lexan sheets were treated identically, it is conceivable that the apparent lack of change in ionization rate from the top to the bottom of the stack could be caused by systematic changes in sensitivity with depth due to subtle differences in the environmental histories of different sheets.

In Fig. 1 we show the etching data in triplicate. Also shown in the upper portion of Fig. 1 is the rate of change of ionization of a charged particle with $Z = 83$ and velocity $0.7c$. The ratio of the etching rates at the beginning and end of the Lexan stack is 1.43; an equal and opposite system-

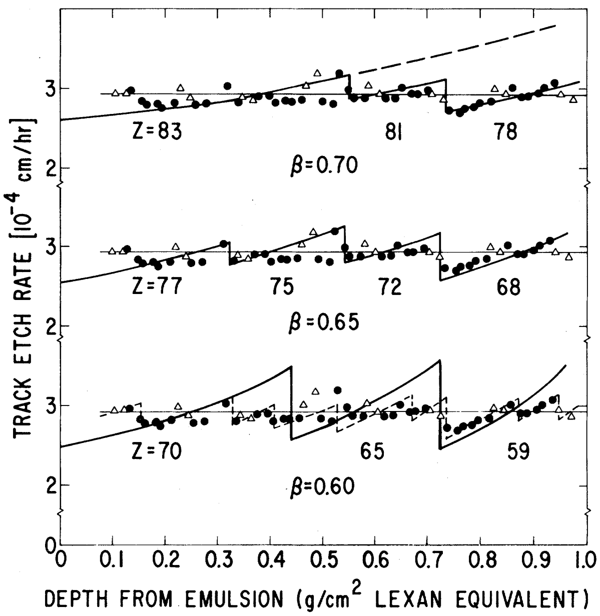

FIG. 1. Data of Price *et al*. (Ref. 1) compared with the behavior expected from nuclei which undergo nuclear interactions. Depth is measured from the midpoint of the nuclear emulsion that was used to infer the velocity. Open triangles are data from a 20-h etch; filled circles are from a 30-h etch and should be given proportionately higher statistical weight. At a velocity βc of $0.60c$, eight nuclear interactions of an atomic nucleus would be needed to fit the data, three interactions at $0.65c$, and two at $0.70c$.

atic change in etching sensitivities would cause this particle to masquerade as a monopole. Lighter, slower moving particles would require a still larger change. More highly charged particles are excluded by the Čerenkov condition that $\beta \lesssim 0.7$.

Although such a systematic change is conceivably due to environmental conditions, our experience with similar plastic stacks suggests that it is highly unlikely. In any event there is a simple experimental test. We estimate that ~20 heavy particles with velocities sufficiently high to maintain essentially constant ionization through the total detector array were collected during the flight. If there is a systematic loss of sensitivity with depth, such particles would appear as anomalous events with obvious decreases in ionization with depth.

If the maximum velocity of $0.6c$ that was deduced by Price *et al.* from the structure of the track in the nuclear emulsion is accepted as the limit, the required change in etching rates for a particle slowing down to masquerade as a monopole becomes a factor of 3.65. An environmental effect of this magnitude seems quite unrealistic and the question of the velocity determination becomes critical. However, more extensive published data are needed to allow assessment of the method used to determine the velocity.

A more promising hypothesis is that a heavy atomic nucleus underwent one or more nuclear interactions as it slowed down through the stack of 32 Lexan polycarbonate sheets that monitored the ionization rate. The required interactions would have reduced the ionization level by amounts that canceled the increase due to the slowing of the particle.[6] In this note we evaluate approximately the probabilities for such behavior and note that a critical evaluation of the velocity at the top of the stack is necessary before a firm decision can be made as to the nature of the particle.

We now examine the data for the ~0.9 g/cm^2 of detector located below the nuclear emulsion. The data in Fig. 1 can be fitted by a constant ionization rate equal to that of a relativistic atomic nucleus of charge ~121, or of that of a monopole of magnetic charge $137e$ with $\gtrsim 500$ proton masses and velocity $0.5c$. This statement, which amounts to a 13% downward revision of the ionization level quoted in Ref. 1, is derived from an improved internal calibration[7] and removes the discrepancy apparent in the original work, which attributed an effective charge of $137e$ to a monopole moving with low velocity. The data from the single sheet of Lexan that was analyzed above the emulsion are neglected here. The two etching-rate values in that sheet differed by 30%, an unusually large difference that we take as indicating the presence of an extraneous environmental effect.

A hint that a nuclear interaction might be present lies in the trend of the data, slightly upward from 0.1 to 0.72 g/cm^2 depth, followed by an abrupt downward shift and a second upward trend from 0.72 to 0.96 g/cm^2, mass thickness being measured from the center of the nuclear emussion. Figure 1 also shows the effects on the etching rate of hypothetical nuclear interactions for nuclei with three different velocities at the emulsion: $0.60c$, $0.65c$, and $0.70c$, the first being the quoted[1] upper limit and the last being close enough to the limit[8] set by the Čerenkov film that it might just fail to give a perceptible darkening. The scatter in the data is such that an interaction at 0.72 g/cm^2 depth is by no means demonstrated, but it is certainly not ruled out. The sawtooth-shaped curves in the figure are calculated by first finding the velocity at a given range from range-energy curves,[9] and then using the empirical variation[10] of the etching rate as $(Z/\beta)^4$ to derive a rising segment of a curve. We then select a change in Z at a fixed β that will give a suitable decrease in etching rate to match the data. Z is the effective charge (nuclear charge minus the number of bound electrons). Its value may be less than the nuclear charge, but probably not by more than 1 or 2%, on the basis of the empirical formula that is normally applied[10] but which has not been directly tested in the charge and velocity range of present interest.

The lowest set of curves in the figure corresponds to the highest permitted velocity at the center of the nuclear emulsion according to Ref. 1. The horizontal line, which is appropriate to a monopole, fits the data vastly better than the other solid curve which is drawn for a nucleus that interacts twice; only if multiple interactions are allowed, as shown by the dashed curve (with eight interactions), is a good fit acquired. In contrast, if higher velocities are permitted, either three interactions are sufficient at $\beta = 0.65$ or two at $\beta = 0.70$, the highest velocity that is compatible with reported data on the sensitivity of the Čerenkov film.[8]

In principle the path of an ion that undergoes a nuclear interaction would be slightly deviated from a straight line. Under maximizing assumptions the loss of eight mass units from a lead nucleus at a velocity of $0.6c$ could lead to a $0.3°$ bend in the track. Such a value is observable, but was not seen. However, this failure to observe a bend does not rule out an interaction, since the most likely value of the angle is less than $0.15°$, the smallest deviation that could have been detected.

The probabilities for the appropriate nuclear interactions are clearly critical to deciding whether any of the above sketched sequences are plausible. Ideally we would wish to know the spallation cross sections for each possible high-velocity interaction between the elements making up Lexan (C, O, and H) and the various elements correspondong to $Z = 60$ to 85. The available data[11] are however limited to the cross sections for spallation of ^{83}Bi by protons at $\beta = 0.75$. Fortunately, bismuth is appropriate to assessing the elements of interest since, unlike heavier elements such as thorium and uranium, it is light enough that spallation is strongly preferred to fission, as is found also for still lighter elements. If we restrict our attention to events in which the nuclear charge is altered by one to five charge units, an approximate cross section of 0.6 b is derived, implying an interaction mean free path (λ) in Lexan of 19 g/cm^2. If a more limited range of two to four charge units only is permitted, $\lambda \approx 28$ g/cm^2. The presence of oxygen and carbon will increase the total cross section by at most a factor of 2 as judged by data from ^{14}N bombardments of uranium.[12] Since the fraction of fission is also likely to be larger when a charge-80 nucleus interacts with heavier nuclei, it is possible that less than a factor-of-2 increase in the appropriate spallation products will result. Putting the two factors together, we estimate a best value of λ to be about 19 g/cm^2 with values from 10 to 28 g/cm^2 being possible.

The probability of a single interaction in the ~ 0.9 g/cm^2 of Lexan that has been reported is therefore about 1 in 21, and similarly for the three examples given in Fig. 1 the probabilities that any single event would have two, three, or eight interactions are 2.3×10^{-3}, 1.1×10^{-4}, and 3.3×10^{-11}. These probabilities give the right number of interactions, but do not assure that their spacing along the track is optimized. Inclusion of this consideration would further lower the numbers somewhat, a rough estimate being that factors of $\frac{1}{2}$, $\frac{2}{9}$, and $8!/8^8$ apply for the three cases.

The integrated probability for finding an event of the type described is proportional to the total number of similar tracks of heavy particles that have been studied by various groups. Clearly if enough statistics are collected, eventually a nuclear event will be seen that fits the present[1] observation. From Fig. 9 of Shirk *et al.*[8] we can compute the fractions of the observed flux of heavy nuclei ($Z > 60$) that arrive at balloon altitudes with approximately the three velocities we have considered. For velocities of $(0.60 \pm 0.025)c$, $(0.65 \pm 0.025)c$, and $(0.70 \pm 0.025)c$, these fractions are 4.5%, 7.4%, and 8.5%, respectively. The total numbers of nuclei observed in the charge range 70 to 83 in earlier flights are summarized[13] as 47 (observed in Northern United States) and 85 (observed in Skylab); we estimate from the size and duration of the recent flights[1] that 38 more should be added to give a total of 170, of which 7.6, 12.6, and 14.4 would be expected to lie in the three velocity ranges. The calculated probabilities of eight properly spaced interactions at $0.6c$, three at $0.65c$, and two at $0.70c$ are therefore 6×10^{-13}, 3.1×10^{-4}, and 1.7×10^{-2}, respectively.[14]

The conclusions are straightforward. A large, but not impossible, systematic change in sensitivity as a function of depth could allow a conventional charge-83 particle to masquerade as a monopole if velocities as high as $0.7c$ are permitted. One critical test would be the demonstration that no relativistic particles (as evidenced by the Čerenkov radiation) appear to decrease continuously in ionization as they progress through the stack. The nuclear-interaction hypothesis is extremely unlikely if the upper limit of $0.6c$ is accepted as the velocity of the particle, the probability being less than 3 in 10^{10} for an assumed mean free path of 19 g/cm^2 and still only ~3 in 10^8 with a lower mean free path of 10 g/cm^2. However, if the emulsion track permits a velocity of $0.65c$, then the interaction interpretation is only rather improble and at $0.70c$ would be a reasonable one. Neither of these latter velocities conflicts with presently published data on the sensitivity of the Čerenkov film, and therefore the weight of the argument in favor of the observed particle being a magnetic monopole rests on careful examination of the error limits to the emulsion-based measurement of velocity.

We are pleased to give thanks to P. B. Price and E. K. Shirk for helpful communications both oral and written and for freely encouraging a visit to their facilities in the best scientific tradition. Constructive discussions with C. P. Bean, M. D. Fiske, M. W. Friedlander, I. Giaever, H. R. Hart, Jr., M. Israel, and A. Mogro-Campero are acknowledged.

[1]P. B. Price, E. K. Shirk, W. Z. Osborne, and L. S. Pinsky, Phys. Rev. Lett. 35, 487 (1975).

[2]Summarized by R. L. Fleischer, P. B. Price, and R. M. Walker, *Nuclear Tracks in Solids* (Univ. of California Press, Berkeley, Calif., 1975), Chap. 5.

[3]Reviewed by R. L. Fleischer, H. R. Hart, Jr., I. S. Jacobs, P. B. Price, W. M. Schwarz, and R. T. Woods, J. Appl. Phys. 41, 958 (1970); and by P. H. Eberhard, R. R. Ross, L. W. Alvarez, and R. D. Watt, Phys. Rev. D 4, 3260 (1971). Assumptions concerning the nature of the monopole are, however, inherent in these searches.

[4]E. N. Parker, Astrophys. J. 160, 383 (1970).

[5]Ref. 2, Chap. 2.

[6]Although arrived at independently by one of us (R.L. F.) this interpretation has also been suggested by others including to our knowledge L. W. Alvarez, M. W. Friedlander, and P. H. Fowler. Since the submission of this paper, Alvarez's paper has been issued as Lawrence Berkeley Laboratory Report No. LBL-4260 (to be published in the Proceedings of the Stanford International Conference on Leptons and Photons, Stanford, California, 27 August 1975) and Friedlander's has been published [Phys. Rev. Lett. 35, 1167 (1975)]. Fowler's analysis will appear in the Proceedings of the Fourteenth International Cosmic Ray Conference, Munich, Germany, 15–27 August 1975.

[7]P. B. Price and E. K. Shirk, personal communication.

[8]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).

[9]R. F. Turek, M. S. thesis, Massachusetts Institute of Technology, 1972 (unpublished).

[10]Ref. 2, Chap. 3.

[11]E. T. Hunter and J. M. Miller, Phys. Rev. 115, 1053 (1959).

[12]J. Hudis and S. Katcoff, Phys. Rev. Lett. 28, 1066 (1972).

[13]M. H. Israel, P. B. Price, and C. J. Wadington, Phys. Today 28, No. 5, 23 (1975); also results in the flight used for Ref. 1.

[14]The assumed change in charge for the $\beta = 0.60$ case should probably be reduced to allowing only one charge unit at a time, in which case the cross section drops by a factor of 4 which will reduce the probability for eight interactions by a factor of 4^8, which will further lower the probability of a highly improbable event. In contrast, allowing a change of only two or three units, but not four, at $\beta = 0.70$ will only lower the cross section by 10%, and therefore the probability of two interactions by 20%.