COMMENTS

Comments on the Reported Observation of a Monopole

M. W. Friedlander
McDonnell Center for Space Sciences and Department of Physics, Washington University, St. Louis, Missouri 63130
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It is shown that the cosmic-ray event recently interpreted as the track of a Dirac monopole can instead be plausibly described in terms of the interaction of an ultraheavy cosmic-ray nucleus, having $Z \sim 96$ and velocity $\sim 0.72c$.

The very recent report by Price *et al.*[1] of their observation of a monopole has aroused considerable interest. Clearly this observation, if correct, is of great importance. Accordingly, it is necessary to show that more conventional interpretations of their data can be ruled out. In dealing with a single event, appeals to probability are notoriously dangerous, and even an improbable concurrence of known phenomena must be considered, in competition with the postulate of an entirely new type of particle.

In this note, it will be shown that the published data are amenable to interpretation in terms of the interaction of an ultraheavy cosmic-ray particle, with $Z \sim 96$, leading to the production of a secondary particle with $Z \sim 90$.

The major feature of the observations of Price *et al.*[1] is the apparent constancy of the track etch rate through many sheets of Lexan. This can signal the traversal of either a monopole or an extremely fast charged particle; both of these should exhibit no measurable change in the rate of energy loss. The failure of the particle to register in a Cherenkov detector, and the track characteristics in a nuclear emulsion, then permit the choice to be made between these two possibilities, in favor of the monopole. All of these charge and velocity estimates will be discussed.

In analyzing the data, the track etching calibration is needed. Price *et al.*[1] state that the etch rate dependence on ionization rate is given approximately by

$$V_T = \mathrm{const}(Z^*/\beta)^4,$$

where V_T is the etch rate in microns per hour and Z^* is the effective charge. From their Fig. 2 (reproduced here as Fig. 1 with the additional designation A, B, C), I have made careful measurements of the parallel scales of the etch rate and apparent charge and have found that the cali-

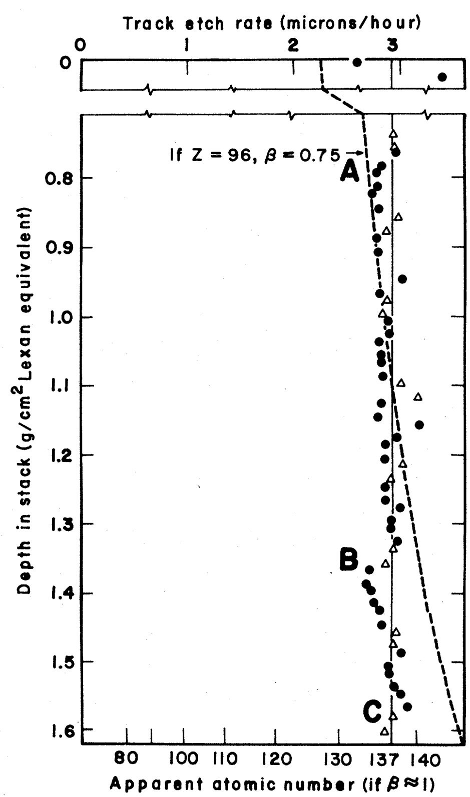

FIG. 1. Figure 2 of Ref. 1, showing the segments now being discussed in terms of a cosmic-ray primary (AB), an interaction (near B), and the segment due to a heavy second particle (BC).

bration is well represented by

$$V_T = 0.97(Z^*/\beta)^{3.5}.$$

This fit has been used in the remainder of my analysis.

Price *et al.* included a dashed line to show how the ionization (and etch rate) would change for a particle with $Z = 96$ and $\beta = 0.75$ traversing the stack of Lexan sheets, and this line deviates substantially from the observed points at the lower end. This is adduced as supporting the rejection of the interpretation in terms of a single particle that is slowing down. If, however, we consider that an interaction occurred near B, then the dashed line cannot be rejected out of hand as a representation of the points in the segment AB. Slightly different values of charge and velocity would give similar fits; for example, a particle with $Z = 96$ and $\beta = 0.72$ near A would have the observed etch rate of 2.9 μm/h near A and would then be expected to display an etch rate of 3.2 μm/h near B. While this is not quite as good a fit as a line of constant etch rate, it does not appear to be unreasonable, especially since the expected change in etch rate between A and B will be slightly reduced by saturation effects that are known to exist in Lexan.

Calibrations in this laboratory[2] have shown saturation that was already clear at an etch rate of 3 μm/h. The precise degree of saturation will probably depend on production variations in the Lexan, environmental conditions during its exposure, and the etching regime used; it should be calibrated for each experiment. Without such a calibration no quantitative account has been taken of saturation effects in the analysis in the present paper, but one can make the qualitative observation that these effects will act in the direction of reducing etch-rate differences along a track, at high rates of ionization.

Careful measurement of the positions of the data points in the figure suggests that saturation may indeed already be present. The etch points for 20 h (triangles) have a mean etch rate that is 0.07 ± 0.03 μm/h higher than those for the 30-h etch. This would indicate that the etch cones are not proportionately longer for the longer etch time.

Extrapolating back to the topmost Lexan sheet, the etch rate for the suggested primary particle would be 2.3 μm/h (neglecting saturation effects). Standard errors were not stated by Price *et al.* for the individual points, but can be inferred from their dispersion in their Fig. 2 to be close to ± 0.2 μm/h. In this case, the difference between the extrapolated value of 2.3 μm/h and the uppermost value of 2.7 μm/h might not be significant. The poor agreement observed between the two data points for the same upper sheet suggests that some extraneous factors may have been present for that sheet.

If the segment AB is due to a particle with $Z = 96$ and $\beta = 0.72$ at A, then the expected velocity at B will be $\beta = 0.69$, and one would expect the heaviest secondary particles to emerge from an interaction at B with velocities closely similar to the primary. In fact, the etch rates along segment BC are very close to what one would expect for a particle with $Z = 90$–92, starting at B with $\beta = 0.68$ and slowing to $\beta = 0.66$ by C.

In summary, to explain the nearly constant etch rate in the Lexan between A and B in terms of an ordinary charged nucleus, we require that (i) the etch rate in the single top Lexan sheet be in error by about 10%, (ii) a nuclear interaction occurred near B in which the charge of the nucleus was reduced so that Z/β (the factor that controls the ionization and thus the etch rate) was very similar for primary and secondary particles over the observed track lengths, (iii) expected changes in etch rate are reduced by saturation, and (iv) the velocity be as high as $0.72c$.

The expected change in velocity of the particle (and etch rate) depend very sensitively on the assumed initial velocity. Price *et al.*, on the basis of the emulsion measurements and the reported absence of a Cherenkov signal, have set an upper limit at $\beta = 0.68$. This claimed upper limit, and the estimate of $\beta = 0.5$ from the emulsion measurements, will now be shown to be less rigid than claimed by Price *et al.*

The only detailed report of the fast-film Cherenkov technique, by Pinsky *et al.*,[3] contains a figure that shows the response of the Eastman Kodak 2485 film, for Cherenkov light from particles of various charges, for $\beta = 0.85$. Given the velocity dependence of the Cherenkov yield, $1 - 1/n^2\beta^2$, the yield at $\beta = 0.72$ will be down by a factor of 3.3 from that at $\beta = 0.85$, and accordingly even a particle with $Z = 100$ would appear to escape detection at $\beta = 0.72$. Further, as is stated by Pinsky *et al.*,[3] the threshold levels in their figure "represent an upper limit," because they "are based on nuclear emulsion results and because of the lower electron density in Eastman Kodak 2485." In summary, it would appear that a velocity as high as $\beta = 0.72$ can be reconciled with the absence of a Cherenkov signal for the "monopole."

In the case of the nuclear emulsion, it would seem that the observations on the very steep track (the precise steepness was not specified by Price *et al.*) are not inconsistent with that expected for the primary now being suggested, and with velocity as high as $\beta = 0.72$. Precise measurements on such heavy tracks are best made with a photodensitometer, but the interpretation is still difficult for very steep tracks. Emulsion contracts in thickness by a factor of ~ 2 during processing while the far less compressible silver filament forming the track must buckle to accommodate this change. As a result, the core thickness is at most a useful guide. There is, in addition, the problem of correcting for loss of δ rays out of the surfaces of an emulsion of finite thickness. At distances from the track core that are comparable to the emulsion thickness, density corrections (for grains produced by long-range δ rays) can amount to a factor of 2,[4,5] and recent work by Hoppe[6] has pointed to a possible underestimate of this correction even when measurements are only 10 μm from the core. In summary, neither the core nor the halo density can be used as an accurate velocity discriminator nor to set close limits on the charge of the particle.

The interaction mean free path, in Lexan, is about 5 g cm^{-2} for a particle with $Z \sim 96$ and mass number ~ 240: The probability of a collision occurring with a 1–2 g cm^{-2} detector is thus not negligible, and the most probable outcome of such an interaction at these moderate energies is the chipping off of a relatively small part of the primary particle.

One final point can be made. In the present experiment, the viability of the suggestion of the interaction rests on the interpretation of the marked discontinuity in the etch rate around B. If the interaction had produced only much smaller secondary particles, none might have been ionizing above the Lexan threshold. No track would then have been detected in the lowest several sheets, and the possibility of an interaction might have been considered. Had there been another nuclear emulsion at the very bottom of the detector stack, all ambiguity would probably have been avoided. In our laboratory, such an interaction has been observed, in a stack in which three emulsions were used along with many plastic sheets, with one emulsion at the very bottom. The preliminary data on this event have been reported[6,7]; revised data and a more extensive analysis will be published.[8] In our interaction, the reason for the abrupt change in etch rate was confirmed when we could find and identify thirteen secondary particle tracks in the lowest emulsion.

Overall, then, it would seem that the reported event of Price *et al.*[1] can find a plausible explanation in terms of the interaction of a primary cosmic-ray particle of $Z \sim 96$ with velocity $\sim 0.72c$. This, in itself, is a matter of considerable interest, since so few of this type of particle have been seen and the lifetime of this nuclide is important in studies of the origin and propagation of the cosmic rays. This event, in addition, demonstrates the continued need for nuclear emulsions.

It is a pleasure to thank Martin Israel for many helpful discussions.

Note added.—Since the publication of the paper by Price *et al.*,[1] it has become widely known that the critical data displayed in their Fig. 2 have been revised. Until these revisions have been published, it will be impossible to evaluate them and accordingly no changes to accommodate them have been made to the present paper, which remains solely a commentary on the original paper. None of the suggested revised data, however, would appear to exclude the alternative explanation being put forward, in terms of a nuclear interaction.

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[2]J. P. Wefel, Ph.D. thesis, Washington University, 1971 (unpublished).

[3]L. S. Pinsky, R. D. Eandi, W. Z. Osborne, and R. B. Rushing, in *Proceedings of the Twelfth International Conference on Cosmic Rays, Hobart, 1971,* edited by A. G. Fenton and K. B. Fenton (University of Tasmania Press, Hobart, Australia, 1972), Vol. 4, p. 1630.

[4]P. H. Fowler, V. M. Clapham, V. G. Cowen, J. M. Kidd, and R. T. Moses, Proc. Roy. Soc. London, Ser. A 318, 1 (1970).

[5]W. C. Wells, Ph.D. thesis, Washington University, 1970 (unpublished).

[6]M. Hoppe, Ph.D. thesis, Washington University, 1975 (unpublished).

[7]G. E. Blandford, Jr., M. W. Friedlander, M. Hopper, J. Klarmann, R. M. Walker, and J. P. Wefel, in *Proceedings of the Thirteenth International Conference on Cosmic Rays, Denver, Colorado, 1973* (University of Denver, Denver, Colo., 1973), Vol. 1, p. 270.

[8]M. W. Friedlander and M. Hoppe, to be published.