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Search for penetrating, highly charged particles at mountain altitude

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We have exposed a 16-m^2 detector consisting of three layers of CR-39 plastic track detector and an aluminum absorber at White Mountain (646 g/cm^2) for one year. We etched these detectors in such a way as to reveal tracks of penetrating particles with ionization rate greater than that of a nucleus with $Z/\beta \gtrsim 15$. Our negative result implies that the flux of electrically charged particles with $Z/\beta > 15$ at a depth of 646 g/cm^2 is less than $\sim 10^{-12}$ $cm^{-2}s^{-1}sr^{-1}$ (90% C.L.) and that the flux of monopoles with magnetic charge $g \geq e/2\alpha$ and velocity greater than $7\times 10^{-3}c$ is less than $\sim 10^{-12}$ $cm^{-2}s^{-1}sr^{-1}$ (90% C.L.).

There are at least three motivations for carrying out a sensitive search for rare particles of large ionization rate capable of penetrating much of the earth's atmosphere without destruction. First is the possibility that magnetic monopoles, whose existence is required in certain unified theories, will be massive enough and slow enough to have eluded detection by previous techniques and yet may be detectable by a suitable new technique.[1] Second is the possibility that collisions of very energetic heavy cosmic-ray nuclei with the atmosphere may produce new forms of matter such as quark-nucleon complexes[2,3] that have long enough lifetimes and interaction lengths to survive to mountain altitude. Third is the possibility that long-lived, tightly bound, highly charged particles may be present at some level in the primary cosmic rays. In each of these cases the earth's atmosphere would serve as a filter to eliminate heavy cosmic-ray nuclei.[4]

Several years ago two of us[5] made the first of a series of exposures of large arrays of CR-39 plastic track detector[6,7] at mountain altitude. Reference 5 contains a description of the techniques for processing and scanning CR-39, a measurement of the energy spectra of helium and lithium nuclei at the summit of White Mountain, California, and an upper limit of 0.27 $m^{-2}yr^{-1}$ (90% C.L.) on the flux of electrically charged particles with $30 \leq Z/\beta \leq 100$ and on the flux of magnetic monopoles with velocity greater than $\sim 0.02c$. In that first exposure, in order to maximize the collecting power per unit detector cost, we deployed almost all of the CR-39 in a single layer, with the drawbacks that we had limited ability to measure β and Z separately and that we could not easily reject background events produced during air shipment of the detectors. There were two such background tracks with $Z/\beta \gtrsim 100$, probably produced by slow, heavy cosmic-ray nuclei that entered the detectors at airplane altitude.

The detector used in the present work consisted of 140 modules, of total area 19.5 m^2. Each module consisted of three layers of 0.6-mm-thick CR-39 from Pershore Mouldings, Ltd., with a 1.5-mm-thick sheet of aluminum positioned between the middle and bottom sheets of plastic. We vacuum-sealed each module in a polyethylene bag and transported it by car to White Mountain. The vacuum sealing turned out to cause a problem, which we will relate below. We exposed the modules in a building at the Barcroft Laboratory (646 g/cm^2) from 14 June 1981 to 4 July 1982 and brought them back to Berkeley by car.

The minimum value of the ratio $s \equiv v_T/v_G$ of track etch rate to general etch rate detectable by an ammonia-gas flow-through technique, for a track at zenith angle θ, is given by

$$s_{\min} = H_i \sec\theta (H_i - H_f)^{-1} ,$$

where H_i and H_f are values of sheet thickness before and after etching. In the previous work[5] the average value of $s_{\min}$ attained was $\sim 1.6\sec\theta$, which led to a minimum detectable value of $Z/\beta \sim 30$ for particles at zenith angles less than $\sim 40°$. In the present work, by supporting each sheet in a Monel mesh frame suspended in the NaOH etch solution (maintained at 70 °C) and by operating the stirring motor at reduced speed, we were able to attain a smaller final thickness ($H_f \sim 125$ to 175 μm) and thus attain a value of $s_{\min} \approx 1.27\sec\theta$. [We discuss below the procedure for relating $(Z/\beta)_{\min}$ to $s_{\min}$.] About 80% of the three-tiered array survived the etching intact; the remainder, consisting of regions of unusually small initial thickness, was unusable either because of sheet fracture during etching or because of the development of an impractically high number of etched holes due to tracks of slow He nuclei.

Using a stereomicroscope we inspected each hole located by the ammonia scan; we superimposed sheets from the same module and looked for coincidences. The requirement of a triple coincidence ensured that background tracks produced during air shipment of the plastic from the manufacturer could be rejected. The further requirement that any triply coincident etched tracks have the same conical shapes, indicating an unchanging value of Z/β (see, e.g., Ref. 7), ensured that events due to slow, locally produced secondary nuclei would be rejected.

We found no triple coincidences in the usable area of 15.6 m^2.

To establish the minimum value of Z/β for which the flux limit implied by this negative result applies, we calibrated each sheet by measuring the density of single etched cones due to protons that stopped in that sheet and the density of colinear pairs of opposing etched cones due to protons (plus deuterons, tritons, and a small contribution from He isotopes) that penetrated the sheet without stopping. Details of the method of determining Z and β from measurements of etch pit dimensions are given in Ref. 5. From the measurement of the proton momentum spectrum at 710 g/cm^2 by Kocharian, Saakian, and Korakosian,[8] scaled up by a factor $e^{-646/125}/e^{-710/125} = 1.67$ to correct for the difference in altitude of their experiment and ours, we obtained the relation between reduced track etch rate s and Z/β shown in Fig. 1. The shaded curve shows the range of responses for the present experiment, and the dashed curve shows the response obtained for the CR-39 used in the previous White Mountain exposure.[5]

We found that the significantly lower sensitivity (especially at low Z/β) of the present detectors than of those used in Ref. 5 is largely due to their prolonged exposure in vacuum-sealed bags. (The other detectors were exposed in air.) The detectors in bags with faulty seals had a much higher density of proton etch pits than those in bags with a good vacuum. By irradiating sheets with relativistic neon ions after the initial etch, doing a second etch and examining the neon-etch-pit sizes, we established that the reduction of sensitivity while in the vacuum was permanent. It has long been known[9] that prolonged exposure of certain plastics such as Lexan and cellulose nitrate in high vacuum reduces sensitivity to charged particles. What is surprising here is that for CR-39 the long-term reduction in sensitivity is significant even for a crude vacuum.

Despite the lower sensitivity of the present detectors, we were able to reach a lower detectable value of Z/β than in the previous experiment, by virtue of the greater reduction of thickness resulting from prolonged etching. From Fig. 1 we see that the value $s_{min} = 1.27$ corresponds to $(Z/\beta)_{min} \approx 15$ for the present detectors.

The ammonia-scan technique[9] requires that etched cones from opposite surfaces connect to form a hole, so that tracks at a large zenith angle are detectable only if s is large. Thus, our upper limit on the fluxes of various hypothetical particles, when solid angle is included, depends on the minimum value of Z/β. Table I gives the upper limits, at 90% confidence level, for several values of $(Z/\beta)_{min}$ for electrically charged particles. One sees that accepting trajectories at larger zenith angles leads to more stringent flux limits but raises the minimum detectable value of Z/β.

Table I also gives flux upper limits for magnetic monopoles with velocities above a value β_{min}. The determination of the reduced track etch rate for a monopole of velocity β is highly uncertain. It depends both on a knowledge of the stopping power of monopoles at very low velocity and on the mechanism of track formation at very low velocity. We have used the dependence of monopole stopping power calculated by Ahlen and Kinoshita[10] and have made the most conservative assumption about track formation at low velocities, namely, that it depends on restricted energy loss. There is, in fact, some experimental evidence[11] that track etch rate is greater at velocities below the Bragg peak than would be expected on the basis of a restricted-energy-loss model. Thus, our values of β_{min} for which the upper limits in Table I apply are conservative upper limits. The actual values might be much lower. By studying track production by protons or deuterons at very low velocities one could probably obtain a more accurate value of β_{min}.

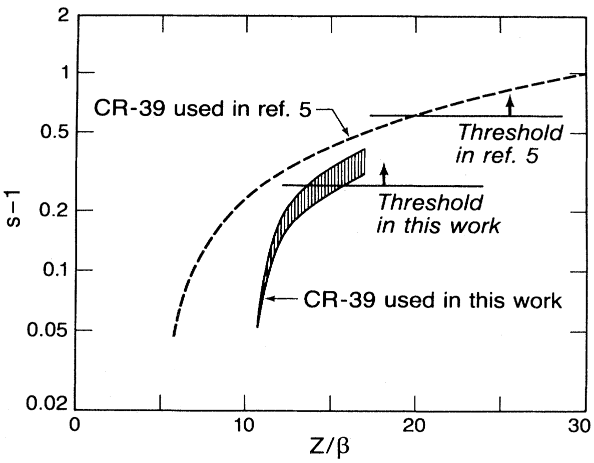

FIG. 1. Responses and detection thresholds for CR-39 detectors used in Ref. 5 and in this work. Although the CR-39 used in this work was less sensitive than that in Ref. 5, by etching for a longer time we were able to detect particles with Z/β lower than possible in Ref. 5.

From the results in Table I we conclude that it is extremely unlikely that the primary particles leading to Centauro interactions[12] at mountain altitude are particles with Z/β greater than ~ 15. From Ref. 5 the ratio of the flux of parent particles to the rate of Centauro events is given by

$$R = \exp(\delta/\lambda_{int}) - 1 \quad ,$$

where $\delta \approx 50\ g\,cm^{-2}$ is the thickness of air over the emulsion chamber[12] in which a Centauro event is detectable and λ_{int} is the interaction mean free path of the parents. Only if

TABLE I. Flux upper limits (90% C.L.).

θ_{max}	$(Z/\beta)_{min}$ (if electric)	β_{min} (if magnetic)	Flux ($cm^{-2}s^{-1}sr^{-1}$)
10°	15	> 0.005	$< 4.9\times10^{-12}$
20°	16.4	> 0.006	$< 1.3\times10^{-12}$
30°	19	> 0.008	$< 5.9\times10^{-13}$
45°	25	> 0.012	$< 2.9\times10^{-13}$

TABLE II. Limits on the cross section for production of exotic, metastable, highly charged objects with various threshold energies.

E_0 (GeV/nucleon)	Integral flux of nuclei with $Z \geq 16$, $N(>E_0)$ ($m^{-2}yr^{-1}$)	Upper limit on fraction of interactions leading to an exotic object[a]	Lower limit on cross section for detectability
10	3.3×10^6	2×10^{-8}	50 nb
10^2	8.1×10^4	8×10^{-7}	1.5 μb
10^3	2080	2.5×10^{-5}	50 μb
10^4	52	1.3×10^{-3}	2.5 mb

[a]Defined as having $\tau > 10^{-6}$ s, $\lambda_{survival} \geq 500$ g cm^{-2}, and $Z > 15$, so as to be detectable in CR-39 with an ammonia scan.

λ_{int} were less than ~ 100 g cm^{-2} of air could Centauros be produced at their observed rate without our having detected some of the highly charged surviving parents.

There is considerable interest now in the possibility of producing metastable droplets of quark matter of baryon-saturated fractional charges called quark-nucleus complexes[2] in nucleus-nucleus collisions at very high energies. Gyulassy[13] has estimated that the phase transition to a quark-gluon plasma may be reached in collisions of heavy nuclei at laboratory energies of $\sim 10^2$ to 10^3 GeV/nucleon. Although such energies are far beyond those available at the LBL Bevalac or planned in the next generation of heavy-ion accelerators, there is a substantial flux of heavy nuclei at such energies impinging on the earth's atmosphere. Table II shows the flux of cosmic rays with $Z > 16$ at energies above various levels, the minimum fraction of interactions leading to an exotic object detectable in our CR-39 array, and the minimum cross section for detectability in our present experiment. It should be noted that our present CR-39 array has allowed us to set useful limits on the cross section for producing highly charged, metastable particles in nucleus-nucleus collisions at laboratory energies as high as 10 TeV/nucleon. The key ingredients in this search are the availability of heavy nuclei extending to extremely high energies, the use of ~ 500 g cm^{-2} of atmosphere to filter out fragments of normal nuclei, and the use of a very large, integrating detector.

In future, larger arrays of CR-39 of higher sensitivity, exposed in air rather than in vacuum and containing an antioxidant to reduce degradation during a year's exposure could be used to search for particles with Z/β as low as ~ 8. A CR-39 experiment would be much less expensive than an experiment involving plastic scintillator or other detector with electronic readout.

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[1]See. e.g., J. Preskill, Phys. Rev. Lett. 43, 1365 (1979).

[2]A. De Rújula, R. C. Giles, and R. L. Jaffe, Phys. Rev. D 17, 285 (1978).

[3]J. D. Bjorken and L. D. McLerran, Phys. Rev. D 20, 2353 (1979).

[4]P. B. Price, F. Askary, and G. Tarlé, Proc. Nat. Acad. Sci. U.S.A. 77, 44 (1980).

[5]K. Kinoshita and P. B. Price, Phys. Rev. D 24, 1707 (1981).

[6]B. G. Cartwright, E. K. Shirk, and P. B. Price, Nucl. Instrum. Methods 153, 457 (1978).

[7]S. P. Ahlen, P. B. Price, and G. Tarlé, Phys. Today 34, (No. 9), 2 (1981).

[8]N. M. Kocharian, G. S. Saakian, and Z. A. Korakosian, Zh. Eksp. Teor. Fiz. 35, 1335 (1959) [Sov. Phys. JETP 8, 933 (1959)].

[9]R. L. Fleischer, P. B. Price, and R. M. Walker, *Nuclear Tracks in Solids: Principles and Applications* (University of California, Berkeley, 1975).

[10]S. P. Ahlen and K. Kinoshita, Phys. Rev. D 26, 2347 (1982).

[11]W. T. Diamond, Schlumberger-Doll Research Center report, 1982 (unpublished).

[12]C. M. G. Lattes, Y. Fujimoto, and S. Hasegawa, Phys. Rep. 65, 151 (1980).

[13]M. Gyulassy, Lawrence Berkeley Laboratory Report No. LBL-15175, 1982 (unpublished).