Can ultrarelativistic heavy nuclei produce Centauro events?

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Negative results of experimental searches for heavy penetrating particles at mountain tops impose strong constraints on the model of Panagiotou, Petridis, and Vassiliou for the production of Centauro-type cosmic-ray events by way of nucleus-nucleus interactions in the upper atmosphere. The quark-matter fireball postulated to produce Centauros must have bizarre properties—an interaction mean free path of $\sim 200\ \mathrm{g\,cm^{-2}}$ and a proper lifetime of $\sim 10^{-7}$ s for an object with $A \approx 50$.

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To explain the peculiar nature of the so-called "Centauro" cosmic-ray events observed in emulsion chambers at Mt. Chacaltaya, Panagiotou, Petridis, and Vassiliou [1] have devised a model in which a heavy cosmic-ray nucleus with energy 10^3-10^4 TeV undergoes a central collision with an air nucleus, creating a "quark-matter fireball" that subsequently hadronizes, through an explosive decay, in the fragmentation rapidity regime. In order for it to survive passage from the upper atmosphere downward to 5200 m, the altitude of Chacaltaya, they propose that the quark-matter fireball has a very high density and thus a very long interaction mean free path. In developing the model, they calculate several thermodynamic and kinematical quantities which are consistent with peculiarities of the observed Centauro events such as the absence of pions and the large transverse momentum of the emitted baryons. They say that their assumptions and arguments do not conflict with any known theory nor contradict any existing experimental data. They conclude by suggesting that Centauro-type events should be looked for at the future BNL Relativistic Heavy Ion Collider (RHIC).

In this Comment, I would like to call attention to experimental cosmic-ray data that threaten the model of Panagiotou, Petridis, and Vassiliou unless the fireball's interaction mean free path is fine-tuned to be $\lambda \approx 190\ \mathrm{g\,cm^{-2}}$ or else its proper lifetime is $\sim 10^{-7}$ s and $\lambda \gg 190\ \mathrm{g\,cm^{-2}}$. In addition, the cross section for the production of quark-matter fireballs must be at least a few percent geometric.

To explain the observation of $\sim 60-\sim 90$ hadrons and no (or few) electromagnetic cascades in the five Centauro events that were discussed in the review by Lattes, Fujimoto, and Hasegawa [2], Panagiotou, Petridis, and Vassiliou propose that a heavy nucleus ($A_{\mathrm{proj}} \sim 60$) collides with a nucleus of nitrogen or oxygen ($A_{\mathrm{targ}} \sim 15$), forming a quark-matter fireball that ultimately explodes into the constituent hadrons. Some years ago, McCusker [3] suggested that a small fraction of iron ($A = 56$) nuclei in the cosmic rays would survive passage through several hundred $\mathrm{g\,cm^{-2}}$ of atmosphere and produce Centauro events *directly* when they interact. This simulated a detailed calculation [4] in which the authors took into account various chains of fragmentation and showed that the flux of surviving heavy nuclei is too low by a factor of $\sim 10^{-10}$ to account for Centauros. Panagiotou, Petridis, and Vassiliou avoided this problem by conjecturing that, although the initial collision of the heavy cosmic-ray nucleus does occur very high in the atmosphere, for a central collision the resulting fireball consists of a very dense object that penetrates several hundred $\mathrm{g\,cm^{-2}}$ of air before exploding into the fragments that are detected in an emulsion chamber. They do not specify whether the explosion is spontaneous, characterized by a lifetime τ, or is induced in a central collision with an air nucleus, characterized by an interaction length λ.

In 1980 my colleagues and I made two mountain-top exposures [5,6] of a track-recording plastic film called CR-39, one goal of which was to test the hypothesis that Centauro events might be initiated by a highly charged particle. Recently another group has carried out a similar search [7] with an area-time factor an order of magnitude larger than ours. The idea in those three experiments was to expose, for a long time, a large area of a detector that would record only particles with an ionization rate corresponding to that of a relativistic nucleus with $Z \geq 20$, in order to search for a new class of highly charged particles with anomalously long interaction mean free paths. This type of detector complements emulsion chambers, which are useful for detecting electromagnetic and nuclear cascades but cannot be used to search for tracks of individual heavy nuclei.

The following two equations, together with Fig. 1, explain the concept of the searches with CR-39 and provide two constraints on the value of the interaction length of the fireball in air.

The flux of Centauro events is given by

$$\phi_{\mathrm{Cent}} = f_c \phi_{Z \geq 17} \exp(-z_1/\lambda)[1 - \exp(-\delta/\lambda)] , \tag{1}$$

where f_c is the fraction of the total inelastic cross section for a nucleus with $A = A_{\mathrm{proj}}$ to have a central collision with a nucleus with $A = A_{\mathrm{targ}}$ and produce a quark-matter fireball, $\phi_{Z \geq 17}$ is the flux of primary cosmic-ray nuclei with $Z \geq 17$ in the energy interval 10^3-10^4 TeV [$\sim(20-200)A$ TeV, if $A \approx 50$], z_1 is the path length in air through which the fireball passes from the point of its creation to the point where it explodes, λ is its interaction length in air, and δ is the thickness of the air layer within which the fireball can explode and lead to an event recog-

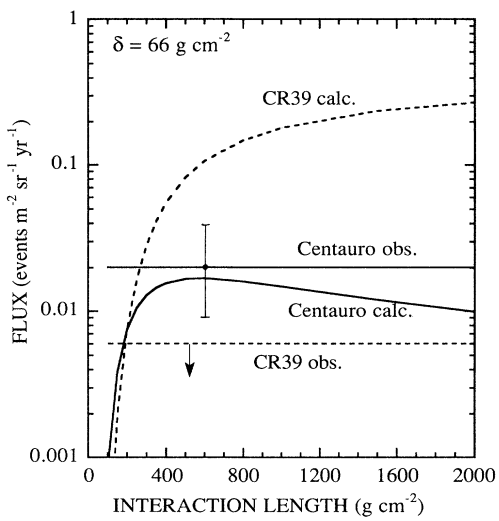

FIG. 1. Constraints on interaction length of the pre-Centauro fireball. The two dashed curves show the combined upper limits of Refs. [5–7], labeled as CR39 obs., and the calculated flux of quark-matter fireballs, labeled as CR39 calc. Comparison of the two curves leads to an upper limit $\lambda \leq 200$ g cm^{-2}. Comparing the observed Centauro rate (solid line with an error bar) with the calculated Centauro rate (solid curve) gives a lower limit $\lambda \geq 230$ g cm^{-2}.

nizable as a Centauro in an emulsion chamber. Following Panagioutou, Petridis, and Vassiliou, we tentatively adopt the value $f_c = (R_{\rm proj} - R_{\rm targ})^2/(R_{\rm proj} + R_{\rm targ})^2 = 0.054$, the geometric requirement for complete overlap of the two nuclei, as an estimate of the fraction of collisions at ultrahigh energies that lead to a quark-matter fireball. For the flux of heavy cosmic-ray nuclei in the energy regime in which Centauro events are seen (10^{15}–10^{16} eV), we use $\phi_{Z \geq 17} = 8$ m^{-2} sr^{-1} yr^{-1}, based on data of Burnett *et al.* [8] for nuclei with $Z \geq 17$. We estimate the uncertainty in this flux to be less than a factor of 2. For z_1, we assume that the fireball is produced at an average depth of 15 g cm^{-2} in the atmosphere (the interaction length for Fe in air), that it explodes at an average distance above the emulsion chamber tentatively taken to be $\delta = 66$ g cm^{-2} (see below), and that its average zenith angle is 30°, thus, $z_1 = 540/\cos 30° - 15 - 66 = 543$ g cm^{-2} (where 540 g cm^{-2} is the depth of Chacaltaya in the atmosphere). The value of δ is that thickness of air above the emulsion chamber within which a quark-matter fireball can explode and be detected as a Centauro event. Estimates of the height of origin of the seven Centauros are 50, 80, 230, 500, 500, 800, and 2800 m above the emulsion chamber [2,9]. Based on this distribution, we assume unit efficiency for detection at heights from ~ 50 to ~ 1000 m and very low efficiency for detection of Centauros initiated at greater heights. Thus, we omit the seventh Centauro event and take $\delta = 66$ g cm^{-2}, corresponding to an interval of 950 m. In Eq. (1) we leave λ as a free parameter.

In Fig. 1 the solid curves compare the flux of Centauro events at Mt. Chacaltaya as a function of λ, calculated from Eq. (1), with the observed Centauro rate, based on six of the seven events observed at Chacaltaya [2,9]. The error in the observed rate indicated by the bar gives upper and lower limits at 90% confidence level as estimated from inverse Poisson statistics [10]. Within this error, and with the tentative choices of f_c and δ, the observed and calculated rates are compatible, provided $\lambda \geq 230$ g cm^{-2}.

The flux of quark-matter fireballs that could be detected in a CR-39 array *before* they explode into Centauros is given by

$$\phi_{\text{CR-39}} = f_c \phi_{Z \geq 17} \exp(-z_2/\lambda) , \tag{2}$$

where z_2 is the path length in air through which the fireball passes from the point of its creation to the point where it is detected in the CR-39 array. The experiments in Refs. [5] and [6] were done at White Mountain, CA (at depths of 603 and 646 g cm^{-2}, respectively); the experiment in Ref. [7] was done at Mt. Norikura (depth of 700 g cm^{-2}). Again assuming an average zenith angle of 30° and formation of the fireball at a mean depth of 15 g cm^{-2}, we get $z_2 = 631$ and 681 g cm^{-2} for the California experiments and 793 g cm^{-2} for the Japanese experiment. Since by far the most stringent limit is set by the Japanese experiment, we use $z_2 = 793$ g cm^{-2} in Eq. (2).

In Fig. 1 the dashed curves compare the flux of quark-matter fireballs as a function of λ, calculated from Eq. (2), with the null result labeled as CR39 obs., which results from summing the area-time factors for Refs. [5–7], taking into account differences in elevation. One sees that the CR-39 limit, 0.006 m^{-2} sr^{-1} yr^{-1} (90% confidence level), is compatible with the calculated quark-matter fireball flux only if $\lambda \leq 200$ g cm^{-2}. To explain the failure to observe quark-matter fireballs, one needs a short interaction length; to account for the Centauro observations, one needs a long interaction length. Fine-tuning the value of the product $f_c \phi_{Z \geq 17}$ does not relax the inconsistency, since it enters as a factor in both Eqs. (1) and (2). If we allow the value of δ to increase to 100 g cm^{-2}, which corresponds to a height interval of 50–1600 m for detectability of Centauros, the minimum acceptable value of λ for Centauros becomes ~ 190 g cm^{-2}, which is then compatible with the maximum acceptable value of λ for failure to see quark-matter fireballs in CR-39.

We conclude that, by fine-tuning the interaction mean free path of quark-matter fireballs to be $\lambda \approx 190$ g cm^{-2}, requiring that Centauros be detectable for interaction heights between 50 and 1600 m above the emulsion chamber, and requiring that the cross section for production of quark-matter fireballs be $\sim 5\%$ geometric, the heavy nuclei hypothesis can account for the Centauro rate and not conflict with the CR-39 results. If the fireball decays rather than interacts, its proper lifetime must be $\tau \approx 10^{-7}$ s. Both λ and τ are extraordinarily large, implying that the fireball has bizarre properties.

The suggestion by Panagiotou, Petridis, and Vassiliou to look at RHIC for Centauro-type events and for strangelets produced during hadronization of the fireball has merit. Assuming that quark-matter fireballs were formed but not seen in mountaintop CR-39 searches because their interaction lengths were too short ($\lambda < 200$ g cm^{-2}), one could still use CR-39 detectors in the future at RHIC both to look for high-Z quark-matter fireballs with $\lambda < 200$ g cm^{-2} in the fragmentation rapidity region and to look for accompanying strangelets, which would be expected to have smaller Z. The minimum detectable value of Z/β for a strangelet (βc is velocity) is ~ 6 for CR-39.

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[1] A. D. Panagiotou, A. Petridis, and M. Vassiliou, Phys. Rev. D **45**, 3134 (1992).

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

[3] B. McCusker, in *Proceedings of the Sixteenth International Conference on Cosmic Rays,* Kyoto, Japan, 1979, edited by S. Miyake (University of Tokyo, Tokyo, 1979).

[4] P. B. Price, F. Askary, and G. Tarlé, Proc. Natl. Acad. Sci. USA **77**, 44 (1980).

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

[6] S. W. Barwick, K. Kinoshita, and P. B. Price, Phys. Rev. D **28**, 2338 (1983).

[7] S. Nakamura, S. Orito, T. Suzuki, T. Doke, H. Ichinose, K. Kuwahara, and K. Ogura, Phys. Lett. B **263**, 529 (1991).

[8] T. H. Burnett *et al.*, Astrophys. J. **349**, L25 (1990).

[9] Brazil-Japan Collaboration, in *Proceedings of the Twenty-First International Cosmic Ray Conference,* Adelaide, Australia, 1989, edited by R. J. Protheroe (Graphic Services, Northfield, South Australia, 1990), Vol. 8, p. 259.

[10] N. Gehrels, Astrophys. J. **303**, 336 (1986).