PHYSICAL REVIEW D VOLUME 24, NUMBER 9 1 NOVEMBER 1981

Is there new physics in the "mini-Centauro" events?

B. S. Acharya, M. V. S. Rao, K. Sivaprasad, and Srikantha Rao*
Tata Institute of Fundamental Research, Homi Bhabha Road, Bombay 400005, India

(Received 1 July 1980)

We demonstrate, by detailed Monte Carlo simulation with standard interaction parameters as input, that the "mini-Centauro" events reported by the Brazil-Japan group can be understood as due to fluctuations in the high-energy hadron and electromagnetic components of extensive air showers generated by primary cosmic-ray protons. Thus it is not necessary to invoke a new type of interaction to understand them.

The Brazil-Japan collaboration group[1-4] reported, among others, two classes of strange cosmic-ray events, which they call "Centauro" and "mini-Centauro" events, observed in their emulsion-chamber detector exposed to cosmic rays at Mount Chacaltaya (atmospheric depth: 530 g/cm^2). They interpret these events as due to interactions in the atmosphere above the detector of hadrons of energy $\sim 10^{15}$ eV in which about 100 *baryons* in the case of Centauro and 15 *baryons* in the case of mini-Centauro events are produced with an average transverse momentum of 1.7 GeV/c via the formation and decay of fireballs of mass 200 and 30 GeV/c^2, respectively, in the two cases, *with practically no pion production,* suggesting the advent of new physics at these energies. Theoretical attempts[5] are made to explain these phenomena in terms of new states of matter. Experiments[6] are also being planned to look for these events at the forthcoming $p\bar{p}$ colliders at CERN and Fermilab and at ISABELLE. Thus it is appropriate at this time to examine the possibility that these events are due to known processes, particularly their fluctuations. We already explained[7] some of the Centauro events in terms of conventional physics. In this paper we consider fluctuations in high-energy hadron and electromagnetic components of extensive-air-shower (EAS) cascades generated by protons in primary cosmic rays and indeed find that all the observed features of mini-Centauro events can be explained in this manner.

Any explanation of the mini-Centauro events has to account for all the observed features. These are as follows: comparable numbers of high-energy hadrons and γ rays (hereafter the term "γ rays" will be used to denote both γ rays and electrons as is the convention in emulsion-chamber work); large fractional energy content in hadrons; exponential nature of distributions in fractional energy and energy-weighted lateral spread of hadrons; and exponential dependence of the former on the latter. At the outset we note that there is no *direct* evidence that all or even most of the observed hadrons in each event originated from a *single* vertex. Since the observed particles in each event are parallel to each other, they could as well be the products from different interactions in a high-energy nuclear and electromagnetic cascade in the atmosphere. In such a cascade, particles are produced presumably with the normal average transverse momentum[8] of 0.3–0.4 GeV/c in interactions in a wide energy range distributed over the entire atmosphere above the detector. These events, when analyzed under the *assumption* that they are due to a single interaction in which the average transverse momentum is large, would yield an interaction height rather low in the atmosphere and vice versa even though the cascade is in reality initiated near the top of the atmosphere. The energy carried by the electromagnetic component in these cascades is in general greater than that in the hadron component even at the atmospheric depth of 530 g/cm^2. However, due to fluctuations in the cascade development, the reverse situation could occur in a certain fraction of the events as in the case of mini-Centauro and Centauro events.

In order to see whether the detailed features of the mini-Centauro events can be reproduced, we have carried out detailed three-dimensional Monte Carlo simulation of the high-energy hadron and electromagnetic components of EAS due to primary protons. We use as input the scaling model for nuclear interactions and inelastic cross sections rising with energy, which seems to account for the bulk of air-shower data.[9] The details of the model[10] and the method of simulation[7] are given elsewhere. The hadrons are further followed through the emulsion-chamber detector with cross sections for baryons on Pb and C targets given by Roberts *et al.*[11] The cross sections for pions and kaons are taken to be $\frac{2}{3}$ of those for baryons. The total energy E_h transferred during its cascading in the detector to neutral pions by each hadron is then obtained. This is the visible energy of the hadron in the detector. Thus, for each event, the visible energy and the spatial co-

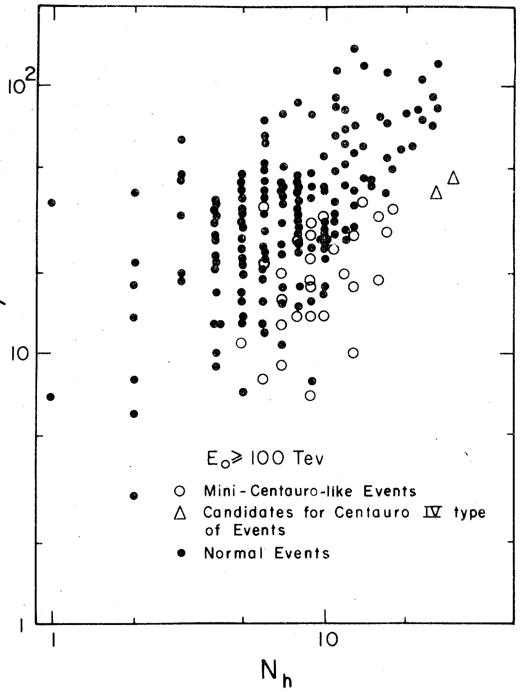

FIG. 1. Scatter plot of number of γ rays, N_γ, vs number of hadrons, N_h, with threshold energy 1.5 TeV for simulated events with visible energy $E_0 \geq 100$ TeV.

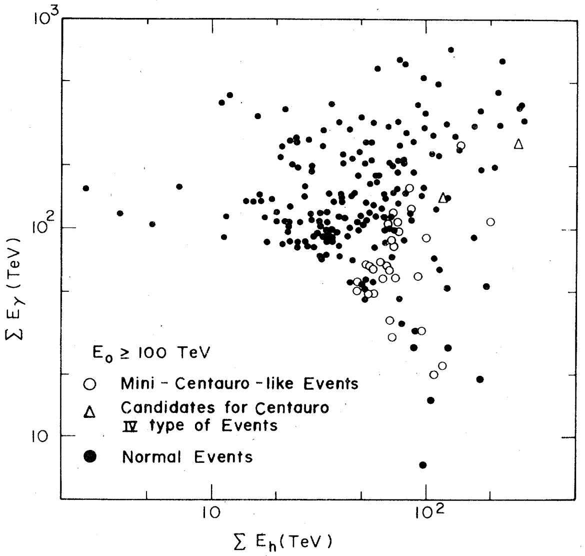

FIG. 2. Scatter plot of the energy content of γ rays, ΣE_γ, vs the energy content of hadrons, ΣE_h for the simulated events shown in Fig. 1.

ordinates of each hadron and γ ray "observed" in the detector are obtained. A total of 850 events are generated in the primary energy interval 10^{15}–10^{16} eV with an assumed differential energy spectrum $f(E)dE \propto E^{-3}dE$.

A cut is made on the simulated events with the following criteria similar to those adopted by the Brazil-Japan (BJ) group[2,3,12] for selecting their mini-Centauro events: $5 \leq N_h \leq 20$, $N_\gamma \leq 40$, $E_0 = \sum E_h + \sum E_\gamma \geq 100$ TeV, $\sum E_\gamma / \sum E_h \leq 2.0$, $E_h^{\max}/E_0 < 0.5$, where N_h and N_γ are the number of hadrons interacting in the detector and γ rays of energy ≥ 1.5 TeV contained within 15 cm from the energy-weighted center, E_0 the total visible energy of the event, $E_h^{\max}$ the maximum hadron energy in the event and the summations are over all particles of each type above the same threshold energy. We are left with 29 events after these cuts; we shall call them mini-Centauro-like events. The lateral spread of the selected events varied from 5 to 20 cm with very few particles outside. Figures 1 and 2 show the scatter plot of N_γ vs N_h and $\sum E_\gamma$ vs $\sum E_h$, respectively, for all the 222 generated events with $E_0 \geq 100$ TeV. We note that the mini-Centauro-like events populate one edge of the distributions. These events then do not represent the average behavior of the cascades, but are due to fluctuations in the cascade development. The mini-Centauro events of the BJ group also populate the same region if plotted on these diagrams. The triangles are candidates for Centauro IV type of events which will be discussed in a separate paper.

Detailed analysis of the mini-Centauro-like events is carried out in the same way as adopted by the BJ group. Figure 3 shows the distribution of fractional energy of hadrons for a sample of 50 events which includes, besides the 29 events mentioned above, an additional sample of 21 events with 50 TeV$\leq E_0 <$100 TeV, selected with the same criteria as above except that $\sum E_\gamma / \sum E_h \leq 1.0$. We note that three of the BJ group's mini-Centauro events have observed energies in this range. The straight line in the figure shows that an exponential function can be fitted fairly well to points in the range $0.03 < E_h/E_0 < 0.2$. The upward deviation of the points from the straight line outside this range, particularly for $E_h/E_0 < 0.03$, is similar to that observed by the BJ group[2].

Figure 4 shows the distribution of normalized energy-weighted lateral spread, $E_h R_h / \langle E_h R_h \rangle$, where R_h is the distance of the hadron from the energy-weighted center. The striking similarity of this figure with Fig. 1 of Ref. 3 can be noticed.[13] We plot in Fig. 5 the fractional energy of the hadrons, $\sum E_h / E_t$ vs their energy-weighted lateral spread $\langle E_h R_h \rangle$. Here $E_t = \sum E_\gamma + f \sum E_h$, where $f = 1/0.7$ is the correction factor for "escape" hadrons following the BJ group. Their mini-Centauro events are also shown in the figure. Clearly the mini-Centauro events and the simulated events

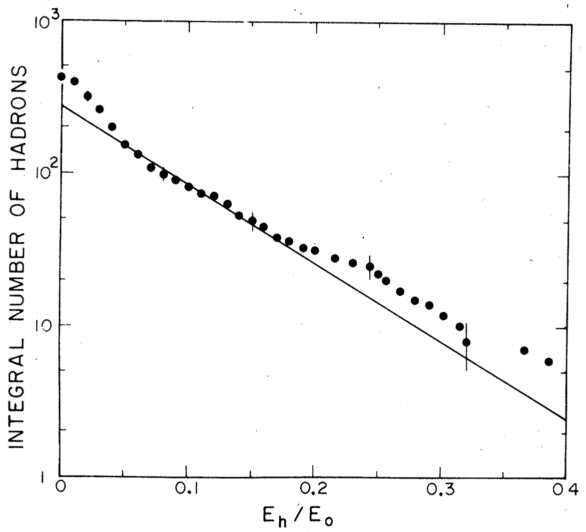

FIG. 3. Integral distribution of the fractional energy of hadrons for the mini-Centauro-like simulated events.

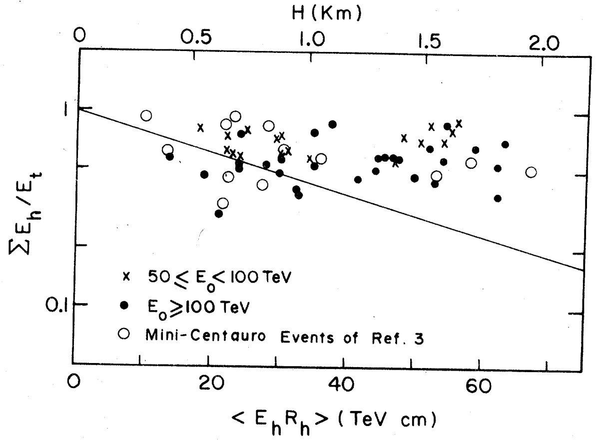

FIG. 5. Diagram of $\Sigma E_h/E_t$ vs $\langle E_h R_h \rangle$ for the mini-Centauro-like events in the two regions of visible energy. The upper scale for abscissa is for the fictitious interaction height above the detector under the assumption $\langle k_\gamma p_t \rangle = 0.34$ GeV/c following the Brazil-Japan group.

cannot be distinguished from each other by their distributions.

In their analysis, the BJ group adds in some events the energies of γ rays in the neighborhood of a hadron to the energy of the hadron. They interpret that the hadron and the γ rays in such groups are the products of an interaction, in the atmosphere very close to the detector, which they call an A jet. In our analysis of the simulated events, we have not combined hadrons and γ rays in this manner. From a detailed examination of the simulated events we find it very difficult to formulate *objective* criteria for identifying A jets since in many cases particles originating from the same interaction are well spread out with other particles interspersing while in several other cases particles originating from different interactions cluster together. In such a case, if A jets are identified according to the criterion of the BJ group,[3] the energy balance would tilt in favor of hadrons, the energy-weighted lateral spread might decrease in some cases, and it would appear as though a mini-Centauro type of interaction has occurred closer to the detector. Reanalysis including such A jets has changed the ratio $\sum E_\gamma / \sum E_h$ in three simulated mini-Centauro-like events with 50 TeV $\leq E_0 < 100$ TeV from 0.54 to 0.09, 0.20 to 0.08, and 0.35 to 0.0 and in one event with $E_0 = 308$ TeV from 0.55 to 0.14.

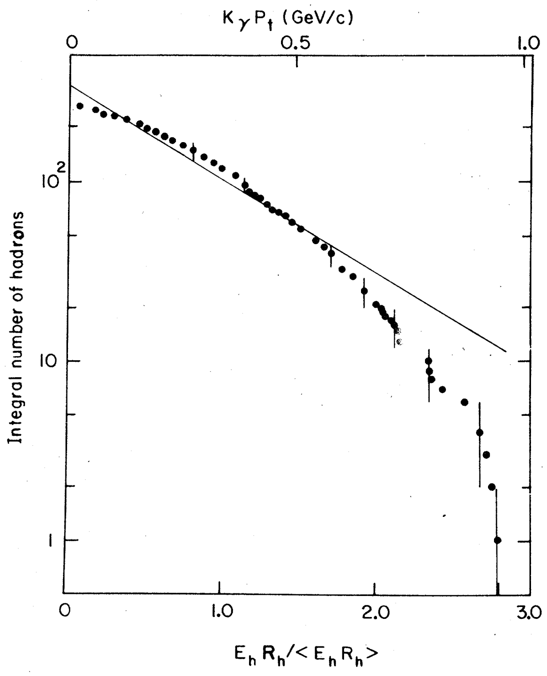

FIG. 4. Integral distribution of the normalized energy-weighted lateral spread of hadrons in the mini-Centauro-like simulated events.

The average number of hadrons with $E_h/E_0 \geq 0.03$ for the 26 simulated events for which the "fictitious" interaction height is less than ~1 km is 5.9, in excellent agreement with the value 6.1 for the ten mini-Centauro events of the BJ group satisfying the same conditions. The percentage of mini-Centauro events, among all events with $E_0 \geq 100$ TeV, in the completely scanned portion of the emulsion chambers,[12] is 16 ± 7 (6/37), in good agreement with 13 ± 2 (29/222) for the simulated events.[14]

There is no compelling reason from the existing air-shower data to drastically alter the usual picture of multiparticle production in which pions are the dominant particles produced. Since the mini-Centauro-like events in our simulations are mainly due to fluctuations in the cascade development rather than the details of the model, we can expect any reasonable model, in which the dominant particles produced are pions, also to reproduce these events. Thus we conclude that there is no need to invoke a new type of interaction in which only baryons are produced to understand the mini-Centauro events.

We are grateful to Professor B. V. Sreekantan and Professor G. B. Yodh for many useful discussions. We thank the Brazil-Japan group for stimulating discussions and for making unpublished data available to us.

---

*Present address: Computer Engineering Services, Ferguson Road, Bombay 400 013, India.

[1] Brazil-Japan collaboration, in *Proceedings of the 15th International Conference on Cosmic Rays, Plovdiv, Bulgaria, 1977,* edited by B. Betev (Bulgarian Academy of Sciences, Sofia, 1977), Vol. 11, p. 453.

[2] Brazil-Japan Collaboration, in *Cosmic Rays and Particle Physics—1978,* proceedings of the Bartol Conference, edited by T. K. Gaisser (AIP, New York, 1979), p. 317.

[3] Brazil-Japan collaboration, in *Sixteenth International Cosmic Ray Conference, Kyoto, Japan, 1979, Conference Papers* (Institute of Cosmic Ray Research, Univ. of Tokyo, Tokyo, 1979), Vol. 6, p. 356.

[4] Brazil-Japan collaboration, in *Proceedings of the 15th International Conference on Cosmic Rays, Plovdiv, Bulgaria, 1977,* edited by B. Betev (Bulgarian Academy of Sciences, Sofia, 1977), Vol. 7, p. 208.

[5] J. D. Bjorken and L. D. McLerran, Phys. Rev. D 20, 2353 (1979); David G. Sutherland, in *Cosmic Rays and Particle Physics—1978,* proceedings of the Bartol Conference, edited by T. K. Gaisser (AIP, New York, 1979), pp. 503–507; J. Dias de Deus and W. A. Rodrigues Jr., Nuovo Cimento 55A, 34 (1980).

[6] David B. Cline and Jean M. Rhodes, in *Sixteenth International Cosmic Ray Conference, Kyoto, Japan, 1979, Conference Papers* (Institute of Cosmic Ray Research, Univ. of Tokyo, Tokyo, 1979), Vol. 6, p. 301. The Bonn/Brussels/Cambridge/Stockholm Collaboration group are planning to look for these events in their UA5 experiment at the forthcoming SPS proton-antiproton collider at CERN.

[7] B. S. Acharya *et al.*, in *Sixteenth International Cosmic Ray Conference, Kyoto, Japan, 1979, Conference Papers* (Institute of Cosmic Ray Research, Univ. of Tokyo, Tokyo, 1979), Vol. 6, p. 289. This work in greater detail will be published elsewhere.

[8] There does not seem to be any compelling reason for very large *average* transverse momentum from extensive air-shower data.

[9] M. Ouldridge and A. M. Hillas, J. Phys. G 4, L 35 (1978); the breakdown of scaling suggested by T. K. Gaisser *et al.*, Rev. Mod. Phys. 50, 859 (1978) does not affect our calculations since the high-energy components of EAS are not sensitive to the central region.

[10] B. S. Acharya *et al.*, in *Sixteenth International Cosmic Ray Conference, Kyoto, Japan, 1979, Conference Papers* (Institute of Cosmic Ray Research, Univ. of Tokyo, Tokyo, 1979), Vol. 9, p. 109.

[11] T. J. Roberts *et al.*, Nucl. Phys. B159, 56 (1979). The cross sections measured by these authors are for neutrons at Fermilab energies. We have used these values for p, $\bar{p}$, and $\bar{n}$ of much higher energies. The cross section for the Pb target given by R. A. Nam *et al.*, in *Proceedings of the 14th International Conference on Cosmic Rays, Munich, West Germany, 1975,* edited by Klaus Pinkau (Max-Planck-Institut, München, West Germany, 1975), Vol. 7, p. 2258 from their cosmic-ray measurements in the energy range 5–20 TeV agrees with these values within errors, though there seems to be a slight increase with energy.

[12] M. Tamada (private communication).

[13] The scale on the abscissa of Fig. 1 of Ref. 3 is wrongly marked by the BJ group (M. Tamada, private communication).

[14] The absolute flux of the mini-Centauro events is difficult to estimate from the published data since the effective area of the detector depends on the lateral spread, which varies from event to event.