Simulation of Centauro events

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Comparison between simulations and emulsion-chamber data on atmospheric interactions of 100–1000 TeV cosmic rays suggests that there could indeed exist an anomalous group of events with very little energy in secondary neutral pions. The group comprises two of the Centauro events from the Brazil-Japan experiment and three mini-Centauros, including one event from an independent experiment. Most events classified as mini-Centauros and three of five Centauros can be interpreted normally. Transverse momenta in the original Centauro event is likely to be about 1 GeV/c per secondary, rather than 1.7 GeV/c as originally claimed.

I. INTRODUCTION

The Centauro events[1] found in the Japan-Brazil emulsion chamber have attracted a great deal of attention because of the anomalous feature that they appear to be due to interactions of about 1000 TeV in which few if any neutral pions are produced even though many secondary hadrons are produced. The multiplicities involved are such that the events cannot be due to statistical fluctuations in the relative number of neutral and charged pions in a single interaction. Because of the complexity of the experimental selection criteria it is desirable to compare the data to simulations in which these are taken into account as far as possible.

Preliminary results of several such calculations were reported at the Kyoto conference.[2–4] Only one of these[2] considered effects of heavy nuclei, and it was not clear what primary spectrum and composition were assumed in generating the events. The simulation of Ref. 3 contained only proton events of very high energy, with the result that most of the simulated showers were larger than the observed events. Only average values of measured parameters were reported in Ref. 4. We report here results of a simulation in which events were generated from a primary spectrum with a large admixture of heavy primaries and with energy thresholds chosen to obtain a set of events in the same size range as the experiment. We compare the simulations with data from all three of the large emulsion-chamber experiments.[5]

In Sec. II we describe the simulation. Section III contains the comparison between simulation and data for the relative numbers and energies of particles in the hadronic and electromagnetic components. In the Conclusion we summarize our results and we also comment on transverse momentum of the Centauro events and on events with multiple cores.

II. THE CALCULATION

The model used for hadronic interactions, as well as the general features of the simulation, are similar to those used in a companion paper on local interactions in the detector.[6] The modifications made here correspond to the special features of emulsion chambers as applied to studies of interactions in the overlying atmosphere. The essential fact is that the detectors are sensitive only to energetic photons. Jets produced in the emulsion chamber within 4 radiation lengths are classified as photons; those with deeper points of initiation are classified as hadrons. Hadrons and photons from the primary and subsequent interactions of a cosmic-ray nucleus in the atmosphere above the detector appear in the detector as a family of parallel jets. The morphology of the events is described more fully in Ref. 7.

The simulation procedure consists of the following steps: (1) Select the mass and energy of a primary cosmic-ray nucleus, (2) compute its cascade in the atmosphere, including nuclear fragmentation and secondary hadronic and electromagnetic interactions, (3) record on magnetic tape the position and energy of each hadron ($\pi^{\pm}$, K, p, or n) and each photon above an energy threshold at the detector, and (4) for each hadron decide whether it interacts in the detector, and if so, compute the fraction K_γ of its energy deposited as visible electromagnetic energy.

Spectrum. The composition and spectra assumed are those obtained by the University of Maryland air shower experiment[8] (see Ref. 7 for explicit parametrizations). Primary energy thresholds of 0.63, 1, 2, 3, and 4×10^6 GeV, respectively,[9] were used for proton, He, CNO, Mg, and Fe nuclei, and the energies were chosen from power-law spectra, $dn/dE \propto E^{-\gamma}$, with $\gamma = 2.71$ for all nuclei except Fe and $\gamma = 2.36$ for Fe. Above 2×10^{15}

eV energy per nucleus all spectra steepen to $\gamma = 3$. Given these spectra we expect the following percentages of incident p, He, CNO, Mg, and Fe, respectively, above the primary energy thresholds stated above: 77%, 13%, 2%, < 1%, and 8%. Because of the small expected contribution of CNO and Mg nuclei, only proton, He, and Fe showers were actually calculated.

Atmospheric cascade. In the case of incident nuclei with $Z > 1$ we computed nuclear fragmentation by selecting actual examples with appropriate incident charge from the data of Freier and Waddington.[10] Pion production was calculated by selecting statistically a number of nucleon-nucleon interactions based on the number of released protons in the particular fragmentation.[10] Each nucleon, kaon, charged-pion, and nuclear fragment (if any) was propagated through the atmosphere allowing for subsequent interactions and assuming an energy-dependent cross section.[11] Neutral pions decay at production to two photons whose cascades we computed statistically based on approximation A of electromagnetic cascade theory.[12]

Energy thresholds. Each hadron with $E_h > 2$ TeV and each photon with $E_\gamma > 1.5$ TeV at the detector was kept.

Visible energy and event selection. The visible energy deposited by each hadron was chosen from an inelasticity (K_γ) distribution. Here K_γ is the fraction of the energy deposited (via π^0 decay) in electromagnetic form by the hadron interaction in the emulsion chamber. We used K_γ distributions with mean (median) of 0.19 (0.12) and 0.33 (0.26), respectively, for nucleon and meson interactions.[13] Hadrons that interact within 4 cascade units after entry into the chamber were classified as photons. We find the energy-weighted center of each event and add up all visible energy inside a circle of radius 20 cm. We choose this radius in light of the size of individual modules in the Chacaltaya emulsion chamber, which are 40× 50 cm.[1] All events with $\sum E_{\text{vis}} > 100$ TeV inside the circle are included in the simulated sample for comparison with the data. Figure 1 compares the response of the detector to primary proton, helium, and iron nuclei. The cutoff at high energy is due to the spectrum and at low energy to inability to produce the required $\sum E_{\text{vis}}$.

III. COMPARISON TO DATA

Centauro events are characterized by an anomalously large fraction of secondary energy in the hadronic component (hence few π^0's in the primary interaction). To assess the anomalous events properly it is necessary to compare them to ordinary events. This was done at the Kyoto conference with results as summarized in the

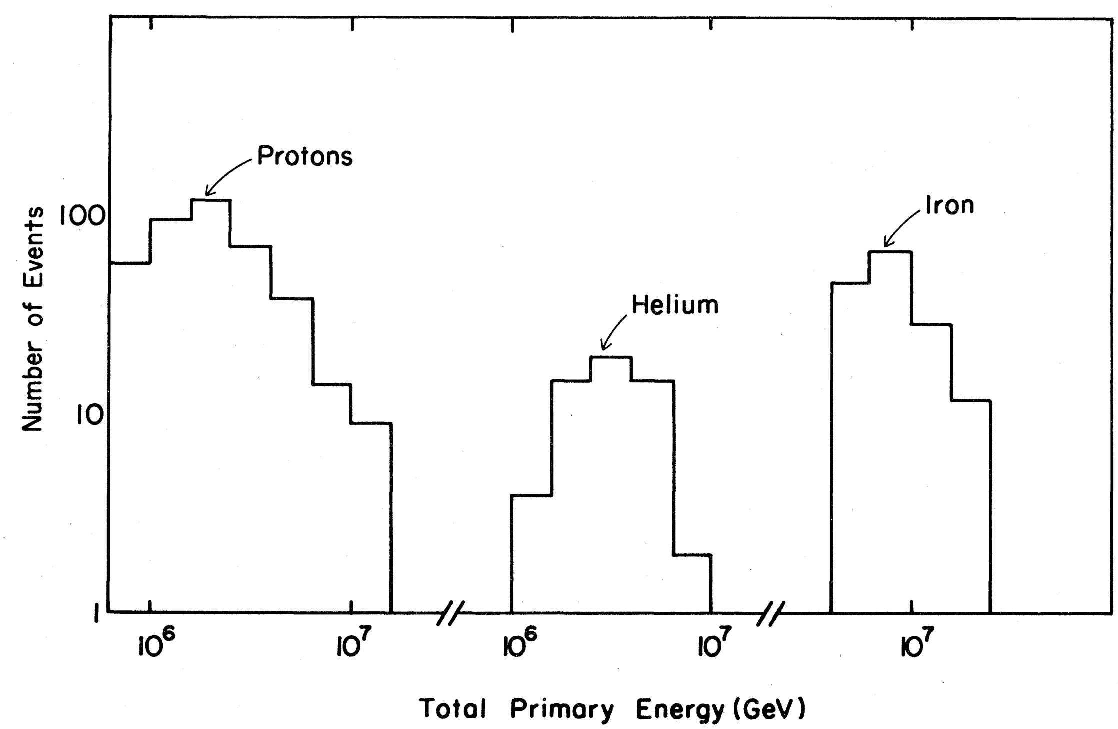

FIG. 1. Response of a large emulsion chamber with a threshold of 100 TeV of primary nuclei of various mass and total energy.

rapporteur talk by Fujimoto.[14] Figure 2 shows the data of the three experiments compared to our simulations.[15] We conclude by inspection of Fig. 2(a) that five events show an excess of hadronic energy well beyond the range of conventional explanation. Two of these are Centauro events (including the original event with virtually no electromagnetic energy) and two were classified as mini-Centauros ($n_h \lesssim 10$) by the Brazil-Japan group. The fifth also has small n_h and is from the Pamir experiment. Only two of these (the Centauros with $n_h \sim 50$) appear outstanding in Fig. 2(b).

The conclusion is reinforced by Fig. 3(a), in which data and simulation are compared for number of events per ln X, where $X \equiv \sum E_h^{(\gamma)} / \sum E_\gamma$. Relative contributions of the three different nuclei are shown separately.[15] Overall normalization is arbitrary, and the total number of events is adjusted to match the total number of simulated events. The peak with $X > 10$ contains the five anomalous events referred to above. It is clear that heavy nuclei tend to give somewhat higher values of X.

The rate of events with $\sum E_{\text{vis}} > 100$ TeV calculated in our simulation from the primary spectrum given in Sec. II is $2\text{–}3 \times 10^{-7}$ m^{-2} sec^{-1} sr^{-1}, whereas the reported rate of such events from the emulsion-chamber experiments is[16] $\sim 10^{-8}$ m^{-2} sec^{-1}. Figure 3(b) compares the results of simulation (with statistical uncertainties) to the experiment on an absolute basis. In this plot and in Fig. 4 one event corresponds to 2.2×10^{-10} m^{-2}sec^{-1}sr^{-1}. The distributions of simulated and experimental events in $\sum E_{\text{vis}}$ are compared in Fig. 4. The experimental scanning efficiency appears to be lower for events near threshold. Some of the difference may also be accounted for if events near the edges of modules in the emulsion chamber are not counted. If, for example, events within 5 cm of the edge of a 40×50 cm rectangle are rejected the collection area is reduced by 0.6. There may be other systematic effects due to uncertainties in the absolute energy scale of the experiment. Moreover, the uncertainty in the absolute flux of primaries at these energies is of the order of a factor of 2 or 3. It is also possible that some further selection criteria may have been used to obtain preferentially those events due to especially high-energy interactions near the detector. We have not included such effects. If it were possible to do so, we might need to modify the conclusion reached above. The rela-

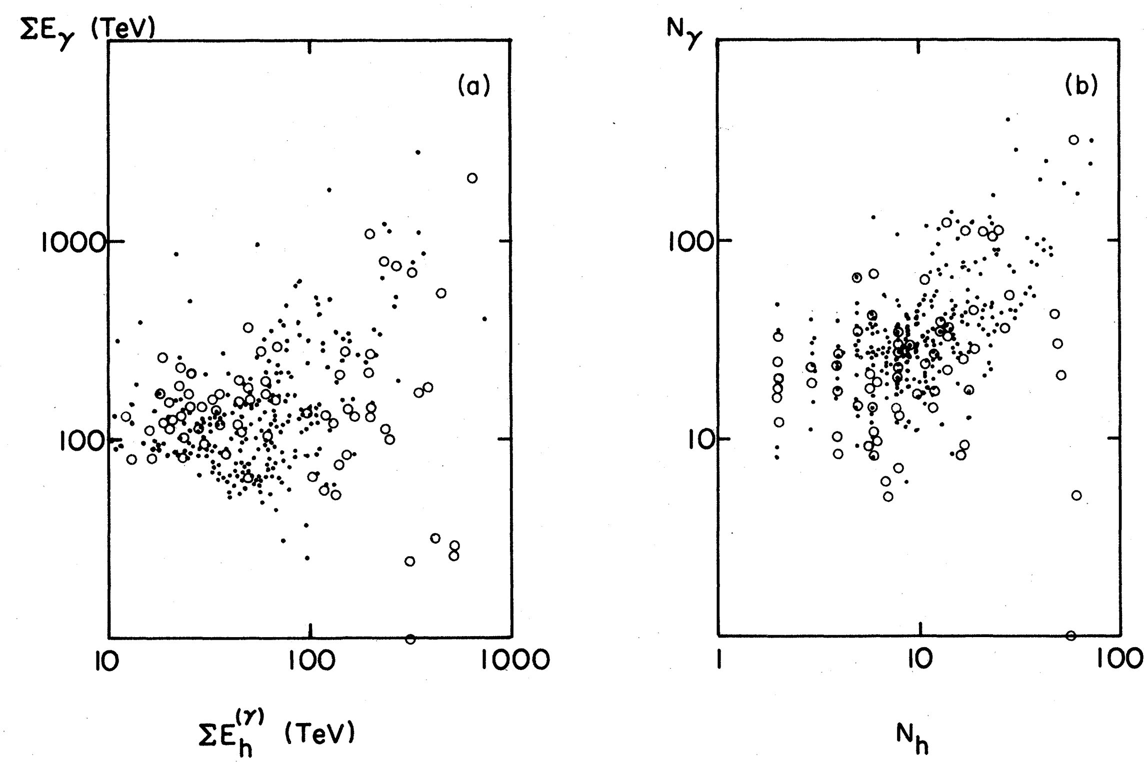

FIG. 2. (a) Scatter plot of total electromagnetic energy vs total hadronic energy. (b) Scatter plot of the number of γ jets vs the number of hadronic jets. Open circles show experimental data. Points show a representative subset of the simulated events.

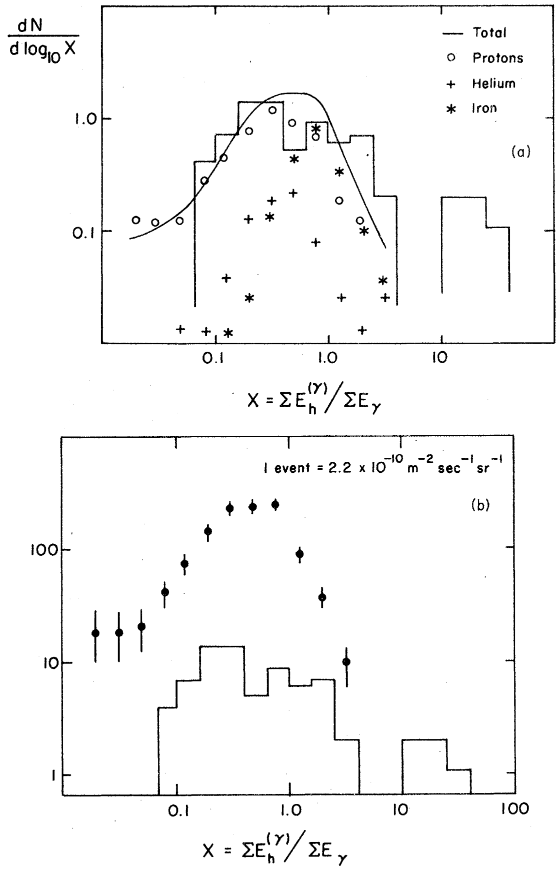

FIG. 3. (a) The distribution of events vs the ratio of hadronic-to-electromagnetic visible energy. The histogram shows the data. Simulations are shown separately for p, α, and Fe. Relative normalization is adjusted to equal areas for experiment and for total simulation. (b) Same comparison as (a) with absolute normalizations. The histogram shows the experimental data. The points with error bars show the total simulation (p, α, and Fe) with statistical uncertainties.

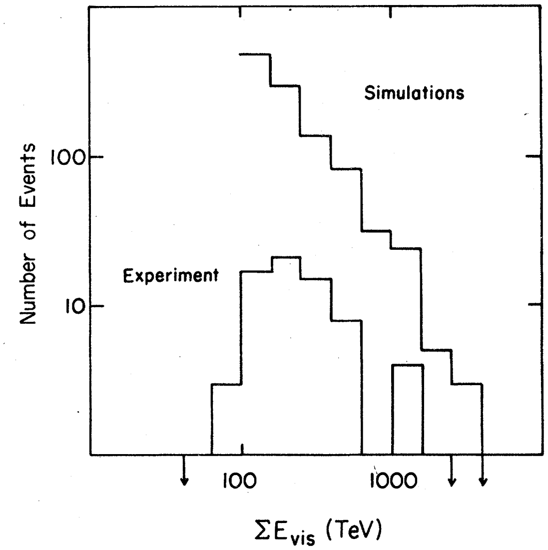

FIG. 4. Visible energy spectra of simulated and observed events.

tive importance of events with large values of X could conceivably be increased by application to the simulation of unknown selection effects. It is, however, difficult to see how this could change our basic conclusion, which is based on 381 simulated events with $\sum E_{vis} > 100$ TeV, as compared to 73 observed events.

IV. CONCLUSION

We summarize the situation as follows. There appears to be a class of events with total visible energy between 200 and 500 TeV which lies beyond the range of any conventional explanation so far proposed. This group comprises five events out of a total of 95 events with visible energy above 100 TeV found in scans of three experiments. The anomalous group includes two Centauro events (the original and one other), the two most energetic mini-Centauros (Fujimoto and Hasegawa, Ref. 1) and one event from the Pamir experiment. Thus at least 5% of the events around 1000 TeV appear to be anomalous. The fraction could be much higher, since Centauro interactions high in the atmosphere would probably be obscured by subsequent atmospheric cascading (see Tamada, Ref. 1). Further study is required, however, to resolve the discrepancy between calculated and observed overall rate of events with $\sum E_{vis} > 100$ TeV.

Because of the low statistics there is no contradiction between the rate of anomalous events among events with $\sum E_{vis} > 100$ TeV reported by the Chacaltaya group (4/50), by the Pamir group (1/30 or 1/100), and by the Fuji group (0/15).[16] Further comparison of the results of the three experiments as well as further data collection is clearly desirable to confirm the existence of the effect.

Two classes of explanations for Centauro events can be imagined: (a) those involving a new kind of interaction of ordinary hadrons beyond some threshold energy and (b) those involving exotic components of the primary beam. In case (a) Centauros, if they exist, would be detectable at $\bar{p}p$ colliders and at ISABELLE (unless the threshold is unreasonably sharp and just beyond the reach of the machine).

In proposing possible interpretations of Centauros, various authors[17] have considered the high p_T of the events as an important clue to the nature of the process. A value of $\langle p_T \rangle = 1.7 \pm 0.7$ GeV/c for hadrons produced in Centauro interactions is claimed.[1] It should be emphasized (as stated in Ref. 1) that the height of interaction could only be obtained for the original Centauro which occurred only about 50 m from the detector. Nothing is known experimentally about the p_T distribution in the other cases. Moreover, since only $K_\gamma p_T$ is actually observed even in this one case, the conclusion is based on the assumption that $\langle K_\gamma \rangle = 0.2$ for all secondary hadrons. In fact, however, there is a systematic increase in $\langle K_\gamma \rangle$ with increasing distance from the core of the event. This effect is due to the steep energy spectrum of the secondary hadrons together with the energy threshold, $E_h^{(\gamma)} = K_\gamma E_h > 1.5$ TeV. Since lower-energy secondaries will be further from the core of the event the threshold will be relatively more important for these secondaries, leading to the increase of $\langle K_\gamma \rangle$ as a distance from the core increases. When this effect is taken into account,[7] one concludes that $\langle P_T \rangle \sim 1$ GeV/c rather than 1.7 GeV/c for the original Centauro event.

The simulation described here is also capable of studying lateral structure of large air-shower cores as seen in emulsion chambers. Dunaevskii[18] has shown that the lateral distribution of γ's within a family is sensitive to the primary composition. Heavy primaries produce energetic γ's at a higher altitude than protons of the same total energy; hence their lateral distribution is broader. Our simulation shows that, for a reasonable fragmentation model, a significant fraction of the γ families of iron primaries are detected. We expect, then, that new information on primary composition may be obtained from the lateral distribution.

Multiple cores with large values of energy-weighted separations have also been seen. The Japan-Brazil group classify as binocular events[19] those with $(E_1 E_2)^{1/2} R > 100$ TeV cm. Here E_1 and E_2 are energies of two distinct subcores separated by R. Interpretation of these events requires careful consideration of the effects of cascading together with the effect of the energy threshold,

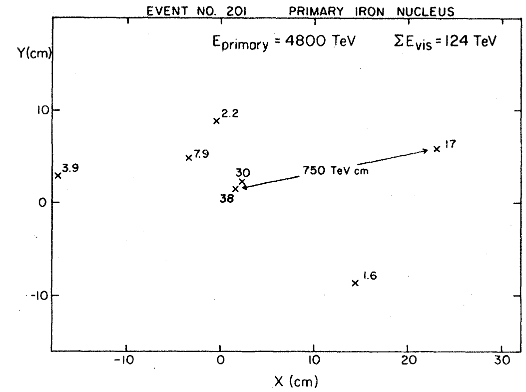

FIG. 5. Target diagram (normal to beam) of an event with multicore structure. There are nine more particles at distances too large to appear. These all have fairly low energies, 1.5–4 TeV.

which can strip the low-energy fringe off a subcore, thus exposing the skeletal structure of the event. We remark here only that it is possible to obtain multiple cores with energy-weighted separations greater that 100 TeV cm without invoking either high P_T or massive fireballs (see Fig. 5).[20] It is unlikely that all the structure reported[19] can be explained in this mundane way. We plan to explore this question in a future paper.

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[2] A. M. Dunaevskii, *et al.*, *in Sixteenth International Cosmic Ray Conference, Kyoto 1979, Conference Papers* (Institute of Cosmic Ray Research, University of Tokyo, Tokyo, 1979), Vol. 7, p. 154.

[3] B. S. Acharya, M. V. S. Rao, K. Sivaprasad, and Srikantha Rao, in *Sixteenth International Cosmic Ray*

Conference, Kyoto, 1979, Conference Papers (Ref. 2), Vol. 6, p. 289.

[4]M. Shibata, in *Sixteenth International Cosmic Ray Conference, Kyoto, 1979, Conference Papers* (Ref. 2), Vol. 7, p. 176.

[5]The three large emulsion-chamber experiments are the Brazil-Japan collaboration at Mt. Chacaltaya (Ref. 1), the Pamir collaboration [S. G. Bayburina et al., in Sixteenth International Cosmic Ray Conference, Kyoto, 1979, Conference Papers (Ref. 2), Vol. 7, p. 75 and Vol. 7, p. 241], and the Mt. Fuji collaboration (M. Akashi *et al.*, *ibid.*, Vol. 13, p. 87 and Vol. 13, p. 98). Further bibliography on this subject may be found in Ref. 7.

[6]R. W. Ellsworth, T. K. Gaisser, and G. B. Yodh, preceeding paper, Phys. Rev. D 23, 764 (1981). For technical reasons an algorithm due to Hilas (private communication) was used here to select energies of secondaries. The output distributions are essentially the same as in our previous work.

[7]T. K. Gaisser and G. B. Yodh, Annu. Rev. Nucl. Part. Sci. 30, 475 (1980).

[8]J. A. Goodman *et al.*, Phys. Rev. Lett. 42, 854 (1979).

[9]Different minimum primary energies can be used for different nuclei to minimize computing time because only events with total visible energy above 100 TeV are selected and the primary energy to produce such an event increases with increasing primary mass (see Fig. 1).

[10]T. K. Gaisser, Phyllis Freier, and C. Jake Waddington, in *Sixteenth International Cosmic Ray Conference, (Kyoto,) 1979, Conference Papers* (Ref. 2), Vol. 6, p. 251; T. K. Gaisser, T. Stanev, Phyllis Freier, and C. Jake Waddington (in preparation). For incident Fe nuclei we assumed on average that 8% of the released nucleons interact to produce pions. For oxygen nuclei the corresponding average is 37%. For library events with pion production it was assumed that at least one nucleon interacted. The actual number of interactions was obtained by giving each of the remaining released nucleons in the event a chance to interact chosen from a Poisson distribution with an average as described above. For α's, where data is unavailable, we assume complete breakup and that on average 1.6 nucleons interact.

[11]We used the cross section given by the solid line in Fig. 12(b) of Ref. 7.

[12]B. Rossi and K. Greisen, Rev. Mod. Phys. 13, 240 (1941).

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[14]Y. Fujimoto, in *Sixteenth International Cosmic Ray Conference, Kyoto, Conference Papers* (Ref. 2), Vol. 14, p. 308. See also the last work in Ref. 1.

[15]Relative fractions of p, He, and Fe events are somewhat different from the numbers stated in Sec. II due to differences in detection efficiencies for different nuclei. The actual simulation consisted of 965 incident protons, 390 α's and 300 Fe nuclei from which there were, respectively, 168, 57, and 156 events with $E_{vis} > 100$ TeV. The calculated efficiency is thus 0.17 for protons, 0.15 for α, and 0.52 for Fe. The contributions of α and Fe have been divided by 2.39 since the incident nuclei should be in the ratio $p:\alpha:\mathrm{Fe} = 0.77:0.13:0.10$.

[16]See Refs. 7 and 14 for summaries of the data rates of the three experiments. The estimate of $10^{-8}\ m^{-2}\ \mathrm{sec}^{-1}$ for the measured flux of events with $E_{vis} > 100$ TeV corresponds to 50 observed families above this energy in an exposure of 150 m^2 yr. If $dn/d\Omega \propto \cos^n\theta$ with $n \sim 8$–10 this corresponds to a vertical flux of 0.7–$0.9 \times 10^{-8}\ m^{-2}\ \mathrm{sec}^{-1}\ \mathrm{sr}^{-1}$. There is an ambiguity in the case of the Pamir experiment due to the fact that a smaller scan is complete whereas a larger scan is for Centauros only. It is not clear in which scan the single anomalous event was found.

[17]D. Sutherland, in *Cosmic Rays and Particle Physics—1979* (Ref. 1), p. 503; J. D. Bjorken and L. D. McLerran, Phys. Rev. D 20, 2353 (1979). See also S. A. Chin and A. K. Kerman, Phys. Rev. Lett. 43, 1292 (1979) and A. K. Mann and H. Primakoff, Phys. Rev. D 22, 1115 (1980).

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[19]S. Hasegawa *et al.*, in *Cosmic Rays and Particle Physics—1978* (Ref. 1), p. 145.

[20]A picture of such an event is also shown by A. Krys., A. Tomaszewsik, and J. A. Wrotniak, Zesz. Nauk. Univ. of Lodz 32, 5 (1980).