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Test of High-p_T Scaling from Cosmic-Ray Interactions up to 400 TeV

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The rate of subcores in cosmic-ray air showers has been measured near sea level with a close-packed 35-m^2 array of spark chambers at Leeds. Auxiliary experiments demonstrate that our transition effects are negligible. The rate of subcores versus shower size is translated into the rate of high-p_T events versus energy of the interacting hadron. Comparison with calculations of Halzen favors p_T^{-4} over p_T^{-8} scaling. The highest energy bin is centered on 350 TeV.

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Cosmic rays provide a hadron beam with intensity sufficient for exploratory study of interactions up to energies of a few 100 TeV, that is, ten times higher than the energy from the super proton synchrotron collider at CERN. Therefore, the results can still be of interest in spite of the limit to accuracy inherent in the cosmic-ray method.

This is a report of an experiment[1] to test models for deep-inelastic interactions by measuring the energy dependence of the cross section for high-p_T production. The results are obtained from the observed rate of subcores in cosmic-ray air showers.

In view of the conflict in results among previous experiments,[2] we first review the case in favor of our results. We then describe the analysis of our data and compare to Halzen's[3] scaling from accelerator data. The results strongly favor the parton model with p_T^{-4} scaling.

In order to interpret any subcore data, a connection must be made between high-energy secondary hadrons produced in the atmosphere and the subcore as observed in a detector. The information used to link the two comes either from computer simulations,[4] or from analytical solutions of cascade shower equations,[5] or from a combination. These have been carried out for air and, in a few cases, the transition effect in overlying roof has been approximated.[6] The latter can be usefully done only if the roof material is nearly uniform and not very thick (in electromagnetic cascade units).

Observational uncertainties can arise from (1) transition effect in roof material, (2) transition effect in the detector itself, and (3) limited spatial resolution if individual particles are not detected. (In what follows, we will refer back to these three categories.)

The initial observation of subcores[7] was made (1) under a thin uniform roof, (2) with a multiwire thick-walled (one inch aluminum) pulse ionization chamber, (3) with detector elements 10×50 cm. Since the thick top cover was uniform, the calculated transition-effect correction (2) was fairly accurate, but the modest spatial resolution (3), and small overall size (~2 m^2), limited the results to evidence for the existence of subcores and to a rough figure for frequency.

Continuing experiments[8] at the University of Michigan utilized thin-walled chambers and extended the array area. The result was better statistics for the frequency of subcores, but limited spatial resolution prevented rigorous tests of models. The next experiments, by other groups, either used thick scintillators as detectors or were done under nonuniform roof structures. We have demonstrated experimentally that a large transition effect is produced when a mockup of a typical roof-girder structure was placed above our Leeds apparatus.[9] The later experiments by other groups apparently had observational uncertainties[9] at least as large as the rate itself. The uncertainties came from (1), (2), and (3) above, singly or in combination.

The spark-chamber array at Leeds[10] gives results that we believe have only minor instrumental uncertainties. (1) The roof is only 2.4 g/cm^2 and uniform. Furthermore, runs were made with added thickness of uniform material and extrapolation to zero thickness shows that the transition effects of 2.4 g/cm^2 are negligible. (2) The detectors themselves have only a 6-mm top glass, which gives only a minor transition effect.[11] (3) The spatial resolution and particle detection efficiency of this type of spark chamber are excellent.[10]

In conclusion, our experimental evidence indicates that our measurement of subcore rate is free of significant instrumental uncertainties.

Data were taken for a net running time of 270 days, with the full array area of 35 m^2 effective nearly all the time. The "beam" intensity was checked by analyzing subsamples of the data for the rate of shower axes striking the array. Our result agrees with more elaborate measurements of shower rate by other groups. Actually, this was not so much a "beam" check as a check on our trigger efficiency and method of calculating shower size from spark-chamber data. The result was reassuring.

The scanning efficiency for detecting subcores was evaluated from independent scans of about 50 000 photos. The result is an efficiency of about two-thirds for all subcores, but it would be much higher for large, well separated subcores, of the sort that other groups have found.

Subcores consist of local concentrations of particles that stand out above the general distribution of particles of the main air shower. The Hillas[12] criterion for statistics with a movable bin was used to decide which concentrations were unlikely to be due to fluctuations. In cases where it was difficult to tell by visual inspection which was the main core and which was the subcore in a given shower, computer fitting was used to find which was a better axis of overall symmetry of all particles in the photograph.

The detailed structure of the subcore was used to calculate the height (h) of origin and the energy (E) of a π^0 that would produce the subcore via an electromagnetic shower in air. This is the method pioneered by Matano *et al.*,[13] which is based on the shower calculations of Nishimura and Kidd.[14] The above, plus the shower axis-to-subcore separation (R), permits the calculation of p_T by means of $p_T = ER/h$.

The average energy (E_0) of the interacting particle that produced the observed subcore is proportional to the energy (E_p) of the incident primary particles, which, in turn, is proportional to the size (N) of the main shower. We assume that N is proportional to the particle density 2.5 m from the shower axis, $\Delta(2.5)$. This procedure was adopted after a study of detailed particle distributions measured at Kiel University.[15] The workers there had an 18-m^2 hodoscope surrounded by sampling scintillators at various distances. Given our restriction of data to a 35-m^2 area with no surrounding sampling scintillators, the Kiel University data indicate that the density at 2.5 m is a good single parameter of shower size. Thus, we use the relation, $N = 1400\Delta(2.5)$, for shower size.

The relationship between shower size, N, and the energy, E_p, of the primary that causes a shower is found[16] from longitudinal development curves that have been deduced from high-altitude observations. Integrals of the curves give total path length of particles in air, which represents most of the energy, E_p, of the primary. The result is $E_p \simeq 10^{10}N$ eV at sea level.

Finally, the relationship between the energy, E_p, of a primary and the effective energy, E_0, of progeny hadrons that are likely producers of interactions from which high-p_T products will appear is found from simulations.[17] It is a factor of about 10.

Overall, the fortuitous result of the above is that the effective "beam" energy, E_0, in gigaelectronvolts is numerically about the same as the shower size, N.

The relative frequency of subcores versus shower size (or "beam" energy) is shown in Fig. 1. There are enough data to give reasonable statistical uncertainty for only two values of p_T, namely, ≥ 1 GeV/c and ≥ 2 GeV/c. The curves are taken from the calculations of Halzen[3] for the scaling extrapolations. The results are normalized at the lowest-energy point, where the statistical uncertainty is least. They are normalized because absolute values are less accurate than relative values for the energy dependence. On the other hand, relative values for the p_T dependence are less accurate, and so the results are normalized separately for $p_T \geq 1$ and $p_T \geq 2$. It is seen that p_T^{-4} scaling fits the data better than p_T^{-8} scaling.

In conclusion, we believe that these results from observation of subcores in cosmic-ray air showers are the only ones to date that are sufficiently free of instrumental uncertainties to constitute a significant test of the form of scaling for high-p_T interactions. Our results favor p_T^{-4} scaling.

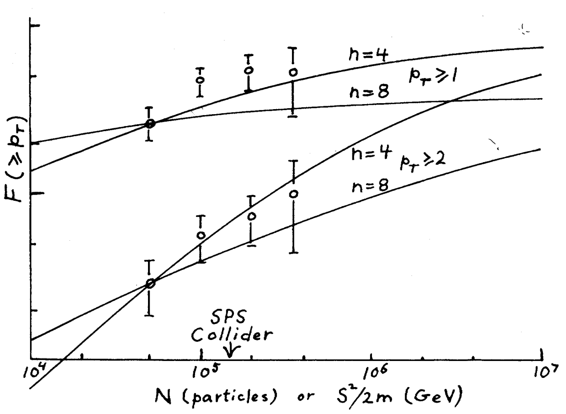

FIG. 1. The relative probability, $F(\geq p_T)$, of production of a high-p_T secondary vs shower size or energy of the interaction. The curves are based on scaling with p_T^{-n} by Halzen (Ref. 3).

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