MEASUREMENT OF THE NUCLEAR-ELECTROMAGNETIC CASCADE DEVELOPMENT IN GLASS AT ENERGIES ABOVE 200 GeV

C.R. Gillespie, R.W. Huggett, D.R. Humphreys
W.V. Jones, and L.B. Levit

Department of Physics and Astronomy,
Louisiana State University,
Baton Rouge, Louisiana 70803, U.S.A.

The longitudinal development of nuclear-electromagnetic cascades with energies greater than 200 GeV has been measured in a low-Z (glass) absorber. This was done in the course of operating an ionization spectrometer at mountain altitude in an experiment to study the properties of gamma rays emitted from individual interactions at energies around 10,000 GeV. The ionization produced by a cascade is sampled by 20 sheets of plastic scintillator spaced uniformly in depth every 2.2 radiation lengths. Adjacent pairs of scintillators are viewed by photomultipliers which measure the mean ionization produced by an individual cascade in 10 layers each 1.1 interaction length (4.4 radiation lengths) thick. The longitudinal development of the cascades has been measured for about 250 cascades having energies ranging from 200 GeV to 2500 GeV. The observations are compared with the predictions of calculations made for this specific spectrometer using a three-dimensional Monte Carlo model of the nuclear-electromagnetic cascade.

1. Introduction. An ionization spectrometer that employs a low-Z material, glass, as the absorber is being used in an experiment to study the properties of gamma rays emitted from individual hadron interactions at energies around 10,000 GeV (Coxell et al. 1969). This experiment is being carried out at the Louisiana State University Cosmic Ray Laboratory which is located at an altitude of 3.7 km near Climax, Colorado. Approximately 250 events involving the incidence upon the apparatus of unaccompanied hadrons in the energy range 200-2500 GeV have been collected. The purpose of this paper is to compare the longitudinal development of the nuclear-electromagnetic cascades observed for these events with the predictions of a semi-empirical model of the cascade development.

2. Experimental. A schematic diagram of the relevant portions of the apparatus is shown in Fig. 1. At the top of the apparatus is a carbon target with layers of neon flash tubes immediately above and below. About a meter below the target is an emulsion chamber also having layers of neon flash tubes immediately above and below.

Beneath the emulsion chamber is the ionization spectrometer. The spectrometer is composed mainly of glass absorber. With such a low-Z absorber, fluctuations in nuclear-electromagnetic cascade development tend to be reduced because such low-Z materials have a small number of radiation lengths per interaction length. Energy is fed into the cascade by strong interactions at a rate determined by the interaction length, but the development and attenuation of the electromagnetic component is determined by the relatively long radiation length.

Ionization within the glass is sampled by 20 sheets of plastic scintillator spaced uniformly in depth every 2.2 radiation lengths. The glass-scintillator combination would seem to be near optimum because glass and scintillator are so similar in those properties relating to nuclear and electromagnetic interactions.

Adjacent pairs of scintillators are viewed by photomultipliers which measure the mean ionization produced by a cascade in each of 10 layers ("sampling layers") of glass each 1.1 interaction length (4.4 radiation lengths) thick. The measured signals from the photomultipliers are converted into mean energy loss rates $\Delta U/\Delta x$ for each sampling layer by employing results of calibrations of the photomultiplier response with muons having known energy loss rates (Gillespie and Huggett 1971).

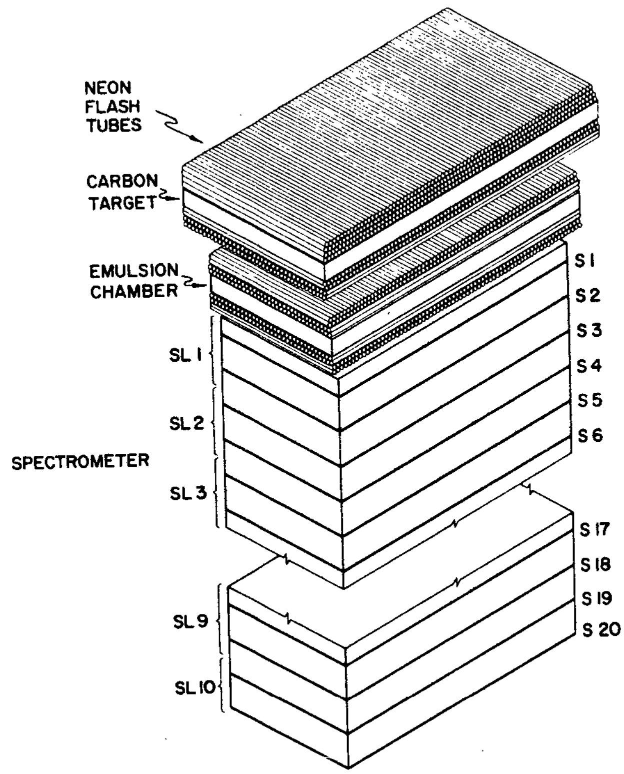

Fig. 1. Schematic diagram of the relevant portions of the apparatus.

3. <u>Results</u>. Because of the limited statistics and the relatively small range of primary energies involved in the observed sample of events, it is not possible in this study to display any convincing variation of cascade longitudinal development with primary energy. Therefore, the observed longitudinal development has been presented in Fig. 2 by superimposing the individual cascade curves measured for each of the events in the sample.

The total observed ionization energy loss E_{ion} within the spectrometer for each event is readily obtained from the observed mean energy loss rates in the sampling layers. The amount of ionization energy E_{out} not observed because of cascade development above the spectrometer and because of the finite depth of the spectrometer has been estimated by extrapolating the observed longitudinal development curve for each event to zero depth and to infinite depth. The superposition of these extrapolations is shown by the broken curves in Fig. 2.

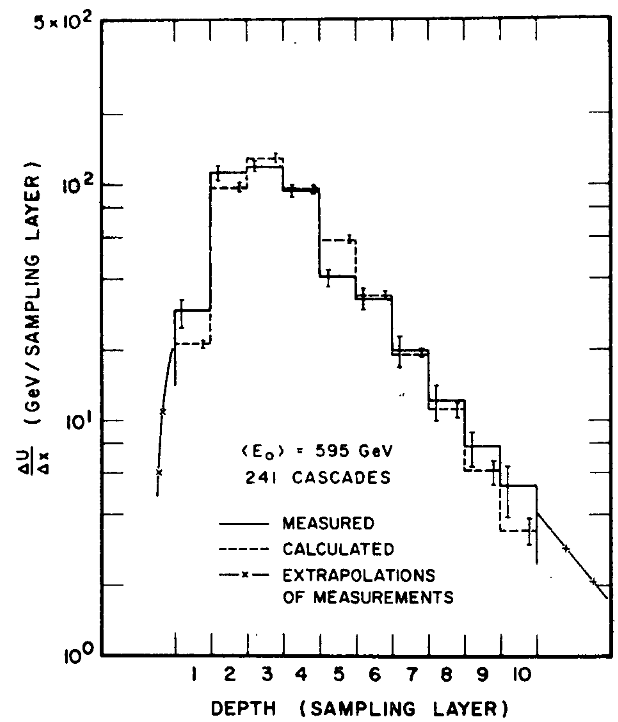

Fig. 2. Superpositions of the observed and calculated longitudinal development curves for the cascades of the sample. The solid histogram is for the observations, and the dashed histogram is for the calculations. The broken curves show portions of the extrapolations to zero depth and to infinite depth.

The expected response of this spectrometer to protons and to pions has been calculated using a three-dimensional Monte Carlo model of the nuclear-electromagnetic cascade (Jones 1969). The calculations were carried out so as to correspond approximately to the energy spectrum of the 241 observed events mentioned earlier. Protons were assumed to comprise 70% of the incident particles and pions, the remaining 30%. In order to correspond to the method of event selection, each of the incident primaries of the calculated events was required to undergo its first interaction in the lower 1/4 of the emulsion chamber or the upper 1/4 of the top sampling layer. The inelasticities of proton and pion interactions with nuclei of the glass were taken to be 0.5 and 1.0, respectively.

The dashed histogram of Fig. 2 shows the superposition of the individual longitudinal development curves predicted by the Monte Carlo calculations for the observed event sample. The agreement between the observations and the calculations is rather good.

The fluctuations in the mean energy loss rates in each sampling layer can be described by the standard deviation σ of $\Delta U/\Delta x$ for each sampling layer. Both the observations and the Monte Carlo calculations indicate that σ for a given sampling layer is relatively energy independent over the range of energies considered here. Hence, the results on the fluctuations are presented in Fig. 3 as single histograms for all observed events and for all calculated events. The solid histogram shows the mean values of σ (in % of $\langle \Delta U/\Delta x \rangle$) measured for each sampling layer. The dashed histogram shows the corresponding values obtained from the Monte Carlo calculations. A random measurement error distribution with a standard deviation of 25% has been incorporated into the calculations for each layer. One sees that the predicted fluctuations systematically tend to be somewhat smaller than those observed.

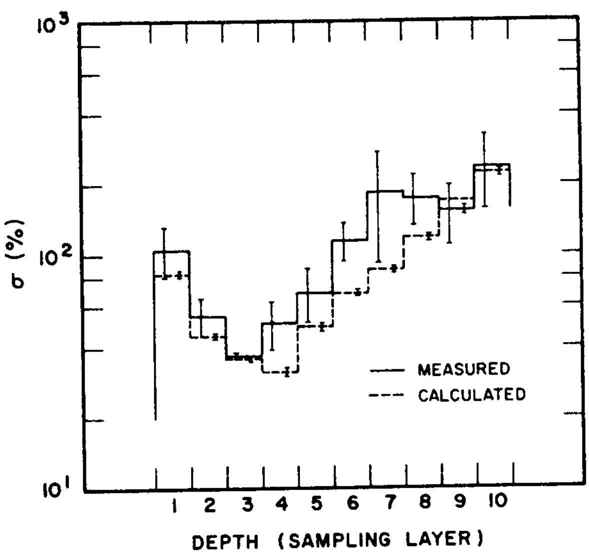

Fig. 3. Fluctuations in the longitudinal development. The solid histogram corresponds to the observations and dashed histogram to the calculations.

In order to obtain the energy E_o of a primary hadron from these measurements, one must add to E_{ion} the energy E_{out} and the unmeasured energy E_d going into heavily-ionizing fragments from nuclear disintegrations within the spectrometer. The correction E_{out} has been obtained, as described earlier, from extrapolations of the observed cascade curves. The results show that E_{out} increases with E_o according to a simple power law over the energy range covered. Values of E_{out}/E_o vary from around 0.1% at 200 GeV to around 4% at 900 GeV. The correction E_d has been calculated using the Monte Carlo cascade model. For the energy range of interest here, the values of E_d obtained from this model are given to within about 2% by the relation $E_d/E_o = 0.54\ [E_o\ (\mathrm{GeV})]^{-0.16}$. From this relation one finds that the values of E_d/E_o range from 22% at E_o = 200 GeV to 15% at E_o = 2500 GeV.

The variation of the maximum $\langle \Delta U/\Delta x \rangle_{max}$ of the average cascade development with primary energy E_0 is shown in Fig. 4. The observations are indicated by the points with error bars. The solid curve indicates the variation predicted by the Monte Carlo model. Neither the observed nor the calculated variation is linear with E_0. The less rapid increase exhibited by the observations at the higher energies is probably due to smoothing caused by grouping the events into energy intervals in order to obtain reasonable statistics for each value of mean energy.

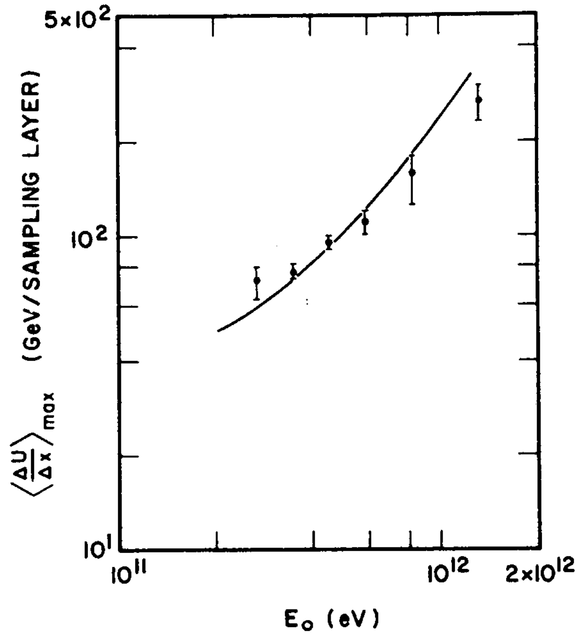

Fig. 4. Maximum value of the mean of the mean energy loss rate vs. primary energy.

Acknowledgements. The assistance of Dr. P.K. MacKeown in the earlier stages of this experiment is gratefully acknowledged. Mr. L.D. Chisholm has played a very important part in designing, constructing, and maintaining the apparatus. This work has been supported by U.S. National Aeronautics and Space Administration Grant No. NGR 19-001-012.

References

Coxell, H., Gillespie, C.R., Huggett, R.W., Humphreys, D.R., MacKeown, P.K., and Pinkau, K. 1969. Acta Phys. Hungar. In press. Presented at the Eleventh International Conference on Cosmic Rays, Budapest. Paper TE 26.

Jones, W.V. 1969. Acta Phys. Hungar. In press. Presented at the Eleventh International Conference on Cosmic Rays, Budapest. Paper TE 27/1.

Gillespie, C.R., and Huggett, R.W. 1971. To be submitted to Nucl. Instrum. Methods.