PHYSICAL REVIEW D VOLUME 26, NUMBER 1 1 JULY 1982

Longitudinal development of cosmic-ray showers

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(Received 20 October 1981)

We report on new measurements of atmospheric Cherenkov radiation in cosmic-ray showers of primary energy 2×10^{15} to 10^{18} eV. The measurements are interpreted with the aid of detailed computer simulations to give the dependence of the depth of shower maximum upon primary energy. The change of depth of maximum between 5×10^{16} and 2×10^{17} eV is found to be greater than expected from plausible models with constant primary cosmic-ray composition.

There have been many attempts to estimate the nuclear-mass composition (NMC) of primary cosmic rays at energies above 10^{15} eV. These have involved many components of extensive air showers (EAS's); for example, the muon/electron number ratio, the lateral distribution from the EAS axis of several components, and the detailed behavior of the hadrons in the EAS core. That no consensus as to the NMC at EAS energies presently exists is due to (a) the difficulty in identifying those experimental quantities which are sensitive to the NMC, (b) the lack of statistical precision in much EAS data (for example, when using local densities to estimate the number of muons in an EAS, Poissonian fluctuations often dominate), and (c) the lack of a suitable and consistent model at the higher energies with which to interpret the data.

Boley,[1] and Fomin and Khristiansen[2] suggested that the longitudinal development of EAS is mapped into the detailed shape of the pulse of optical Cherenkov radiation which is emitted in the atmosphere by shower electrons. The quantities most easily measurable (the lateral distribution and the duration of the Cherenkov-light pulse) are sensitive to the longitudinal development of EAS, are not limited by Poissonian statistics, and can be used to estimate the atmospheric depth of maximum development of individual showers.

Recent papers[3–7] have described the rate of change of electron cascade maximum of cosmic-ray showers with primary energy (the elongation rate) as a means of detecting changes in the NMC. A major difficulty in establishing variations in the elongation rate arises from the necessity of compiling data from a number of widely differing experiments, each requiring a different derivation of the depth of cascade maximum. We report here data from a series of observations in an experiment covering the energy range $2\times10^{15}-10^{18}$ eV. The data were obtained in measurements employing the Cherenkov-light technique and are interpreted using a consistent method and model. The data were recorded during 1978–1980 with the Dugway experiment.[8] An array of eight detectors of flexible geometry has been employed to measure the pulse shapes and lateral distributions of Cherenkov light in showers at zenith angles 0°–45°. The array was deployed with a radius of 400 m optimized for measurements in showers of energy $\sim10^{17}$ eV, 200 m for showers of energy $\sim10^{16}$ eV, and 100 m for showers of energy $\sim3\times10^{15}$ eV. For each shower/array size, appropriate development-sensitive parameters have been chosen; overlap between meaurements at the same primary energy using the different arrays was available and ensured reliable combination of results across a wide energy range.

The measurements are interpreted using Monte Carlo calculations which are specific to the experiment and its environment, and which are successful in providing a consistent representation of many facets of the electromagnetic cascade.[9] The calculated mean depth of cascade maximum is of course dependent on the choice of primary cosmic-ray mass, primary energy, and model of interactions used in generating the hadronic cascades. However, it is found[9,10] that the correspondence between depth of cascade maximum and Cherenkov observable is single valued (for a fixed zenith angle) and independent of these conditions to within the accuracy of the calculations [$\pm(10-20)$ g cm^{-2}]. This arises because the Cherenkov observable depends primarily on the broad features of the electron cascade and not on the detail of the hadronic cascade from which the electrons were generated.

Typical data on the lateral distribution of the Cherenkov photon density are shown in Fig. 1 for near-vertical showers (sec $\theta < 1.05$) in narrow primary energy intervals. The ratio $R(r_1, r_2)$ between the Cherenkov light densities at core distances r_1 and r_2 is sensitive to the depth of cascade maximum. The distances r_1 and r_2 appropriate to, and well measured by, each array size are shown in Fig. 1. We show in Fig. 2 the variations of $R(r_1, r_2)$ with zenith angle for data in showers grouped in three bands of primary energy. The solid lines represent the model calculations[9] appropriate to the zenith angle, altitude, and atmospheric profile of these measurements. Each of these figures (and other examples for other energy intervals) leads to a single accurate estimate of the depth of maximum, which is not dependent upon the exact model of the high-energy hadronic interactions. The values of depth of maximum so obtained[11] are shown in Fig. 3.

Independent data on pulse shapes [full width at half maximum (FWHM) as a function of core distance] from the same experiment are available for showers with primary energy $3\times 10^{16}-10^{18}$ eV. These values allow further independent experimental estimates to be made of the depth of maximum.[12] In this procedure, the FWHM is interpreted by comparing it with model predictions made for its particular core distance and the zenith angle of the shower. This contrasts with the method adopted in previous work,[5,6] in which the lack of appropriate model predictions made necessary the extrapolation of measurments to a single reference core distance and zenith angle before comparison with a restricted model. Values of the depth of maximum at four energies are included in Fig. 3. The depth of maximum deduced from synchronized timing measurements[13] in large showers is also shown in Fig. 3.

The intercalibration of the energy response of the Dugway and Haverah Park arrays using Cherenkov-light densities, and comparison of depths of maximum measured using both arrays in the energy range $10^{17}-10^{18}$ eV, allows the reliable combination of data from both experiments. Published data from four experiments[14–17] at Haverah Park in the energy range $10^{17}-10^{20}$ eV are therefore added to Fig. 3. The estimates of depth of maximum from Ref. 16 have been normalized to pass through 760 g cm^{-2} at an energy of 10^{18} eV, since only the elongation rate, and not absolute

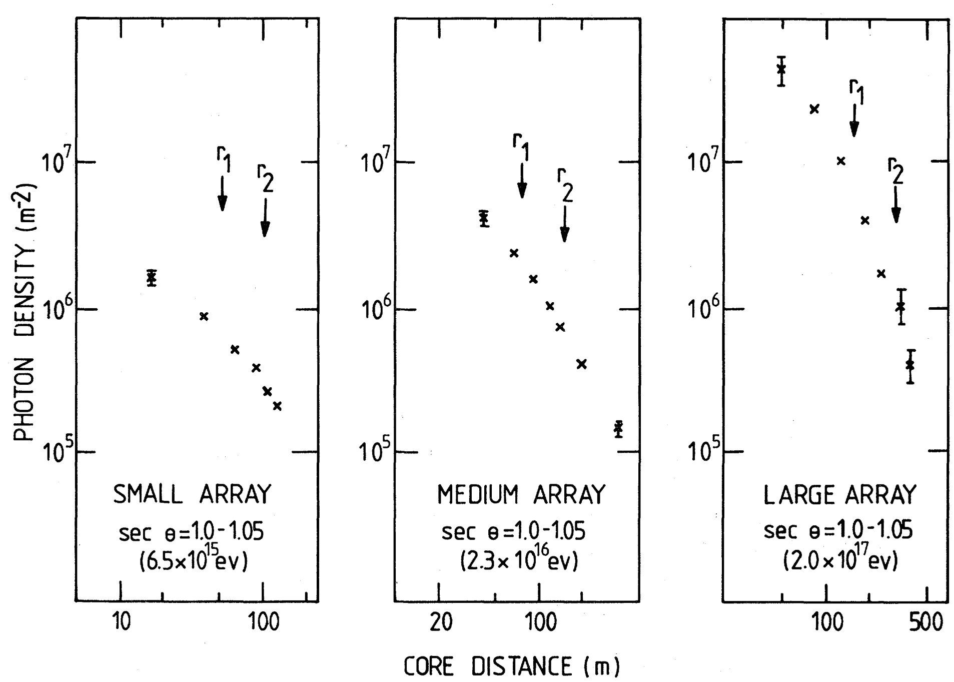

FIG. 1. The measured optical Cherenkov lateral distribution functions for EAS of energies 6.5×10^{15}, 2.3×10^{16}, and 2.0×10^{17} eV. The measurments were made using arrays of three sizes. The distances r_1 and r_2 at which the density ratio $R(r_1, r_2)$ is defined are shown for each array.

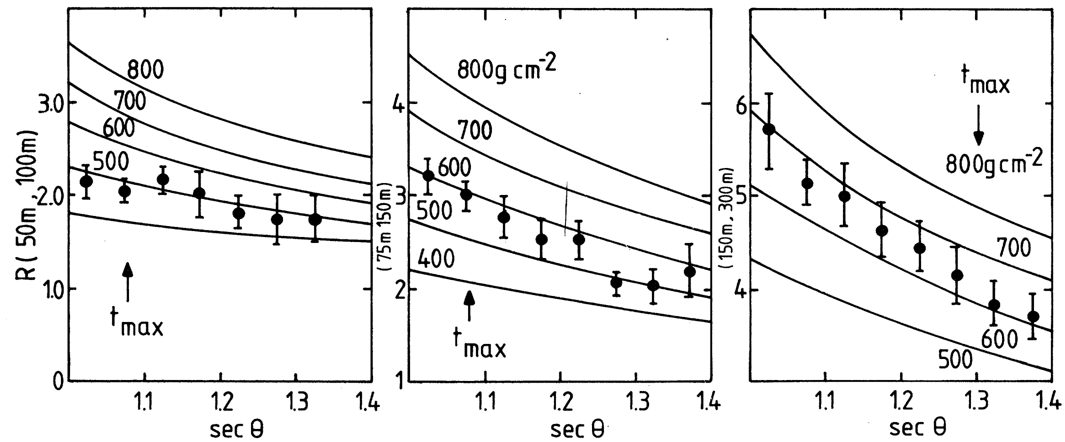

FIG. 2. The measured variation of the density ratio $R(r_1,r_2)$ with zenith angle for showers with primary energies of 6.5×10^{15}, 2.3×10^{16}, and 2.0×10^{17} eV recorded with the three sizes of Cherenkov-light array. Also shown (solid lines) are our computer simulations of these ratios for showers with the indicated depths of electron cascade maximum.

depths of maximum, has been published. Similarly, the data of Ref. 17 yield only a value of the elongation rate, and this result has been normalized to the same point.

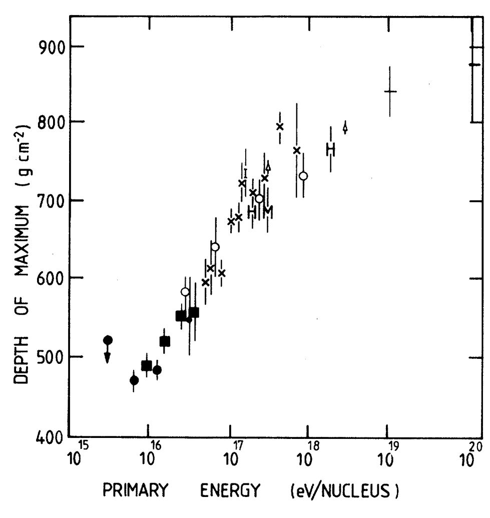

FIG. 3. A compilation of the measured depths of maximum of electron cascades as a function of primary energy. Points denoted by ●, ■, and × are from lateral distribution measurements of the Cherenkov radiation using the small, medium, and large arrays at Dugway (Ref. 11); ○ are from measurements of the FWHM of the Cherenkov signal at Dugway (Ref. 12); I is from the synchronized timing measurements at Dugway (Ref. 13). Other data points are H, our earlier optical Cherenkov observations at Haverah Park (Ref. 14); M, measurements of the muon-core angle (Ref. 15); +, measurements of the deep-water-tank rise time by Walker and Watson (Ref. 16); Δ, interpretation of the deep-water-tank lateral distribution by Craig *et al.* (Ref. 17).

Lateral distribution data from other Cherenkov-light experiments may be interpreted using predictions from the present simultations. At 10^{15} eV (Ref. 18) the derived depth of maximum is 500 $\mathrm{g\,cm^{-2}}$. At energies between 2×10^{17} and 2×10^{18} eV (Ref. 19) values in the range 780–860 $\mathrm{g\,cm^{-2}}$ are obtained, in agreement with the present estimates. Similar interpretations of FWHM measurements in large showers[20] provide an estimate of the depth of maximum of 775 ± 25 $\mathrm{g\,cm^{-2}}$ at an energy of about 3×10^{17} eV. For the energy range $4\times10^{15}-10^{17}$ eV, the other FWHM obsevations[5] are published only as values of the depth of maximum derived using a different model in showers of specified sea-level electron size (rather than primary energy). These results have not been included in Fig. 3 to avoid the possible introduction of systematic errors in the primary energy domain.

A plausible interpretation of the data of Fig. 3 is that the mean primary mass number is close to 56 at 10^{16} eV. Between 5×10^{16} and 2×10^{17} eV the elongation rate is greater than the expectation for constant primary mass composition, implying a reduction in the mean primary mass number. At energies greater than 2×10^{17} eV, the mass number is $\lesssim 10$. At even higher energies the interpretation becomes complicated due to the effect of the increasing cross section upon the depth of maximum. Such behavior of the primary mass number has been suggested[6,7] although the energies at which the changes in the elongation rate occurred have varied. Several experiments to measure the mass composition using other techniques are currently in progress. Measurements of the arrival time distribution of high-energy hadrons,[21] for example, suggest the presence of an increasingly large fraction of heavy nuclei at 10^{15} eV. Our data might be explained by the failure of the magnetic containment within the Galaxy for the (predominantly heavy) primaries at $\sim 5 \times 10^{16}$ eV, leaving a residual extragalactic component of lighter mass at higher energies. This is, of course, not the only possible interpretation. Confirmation of the observed behavior of mass composition with primary energy may come from fluctuation measurements over the same energy range. Extension to lower energies $< 10^{15}$ eV (where little data presently exist) may be achieved by experiments employing Cherenkov-light systems using flux collectors.[18,22]

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