Longitudinal development of muons in large air showers studied from the arrival time distributions measured at 900m above sea level

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ABSTRACT

The arrival time distributions of muons with energies above 1.0GeV and 0.5GeV have been measured in the Akeno air-shower array to study the longitudinal development of muons in air showers with primary energies in the range 10^{17}eV to 10^{18}ev. The average rise times of muons with energies above 1.0GeV at large core distances are consistent with those expected from very high multiplicity models and, on the contrary, with those expected from the low multiplicity models at small core distances. This implies that the longitudinal development at atmospheric depths smaller than 500gcm^{-2} is very fast and that at larger atmospheric depths is rather slow.

Comparison of the mean arrival times of muons with energies above 0.5GeV and the calculation made by McComb et al suggests no serious contribution of muons arising from photon-nucleus collisions to the arrival time distributions of muons with energies above 0.5GeV.

1. Introduction

The Bolivian Air Shower Joint Experiment (BASJE) group and the Tokyo Institute of Technology group carried out a series of experiments to study the longitudinal development of electrons and that of muons by measuring the arrival time distributions both of atmospheric Cerenkov light and of muons, at widely separated atmospheric depths of 550gcm^{-2}(Mt. Chacaltaya) and 930gcm^{-2}(Akeno). The longitudinal development of muons derived from the experiment at Chacaltaya and that of electrons derived from both experiments at Chacaltaya and at Akeno have already been published(1),(2),(3).

In the present paper, we report on the arrival time distributions of muons with energies above 1.0GeV in air showers with primary energies in the range 10^{17}eV to 10^{18}eV observed in the Akeno air-shower array. Also reported in the paper are arrival time distributions of muons, with a lower threshold energy of 0.5GeV, in air showers around 10^{18}eV. On this basis an estimate is made of the contribution of muons arising from photon-nucleus collisions (photoproduced muons) to the arrival time distributions of muons with energies above 0.5GeV, by comparing the mean arrival times of muons calculated by McComb et al(7) with those measued in the present experiment.

2. Experimental

The first run (May 1981-December 1982) was made to measure the arrival time distributions of muons with energies above 1.0GeV in air showers with primary energies around 10^{17}eV. The result of this run was already reported(4).

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In the second run (January 1983-October 1984) the measurement was made both at the M4 muon station (E_μ>1.0GeV) and at the ME3 muon station (E_μ>0.5GeV), which were separated by 100m from each other. Four $4m^2$ shielded scintillation detectors were operated along with a $4m^2$ unshielded scintillation detector at each station (hereafter called muon detector and electron detector, respectively). The inside wall of muon detector was covered with black paper while that of electron detector was painted white, and a 5in fast photomultiplier with 14 stages (Hamamatsu Photonics R1250) viewed a scintillator in the detector. Signals from four muon detectors were added in a circuit through a coaxial cable (11C4AF). A signal from the electron detector was delayed by 1.8μs through a coaxial cable (8C4AF) and then added in the circuit. This combined signal was fed to a waveform recorder (Biomation 8100) with a sampling interval of 20ns. When the local trigger pulse generated by the passage of at least one particle through the electron detector was coincident with a master pulse from the Akeno $4km^2$ air-shower array(5), which observed an air shower with electron size larger than $10^{7.5}$, the combined signal was stored in the recorder.

The time response of the whole system was 16.2ns for rise time between 20% and 70% of the integrated full signal from the muon detector (T_{20-70}).

3. Arrival time distributions of muons with energies above 1.0GeV

In figure 1 average values of T_{20-70} for muons with energies above 1.0 GeV in the second run are presented against core distances, where the data are free from biases arising from the requirement for the local trigger and the limited dynamic range of the pulse height in the recording system. Also shown in the figure are values of T_{20-70} calculated from four models for primary protons with energies of 10^{18}eV and secθ of 1.1. As is seen in the figure, the average values of T_{20-70} at small core distances are consistent with those calculated from low multiplicity models, while high multiplicity models reproduce the present T_{20-70} consistently at large core distances, indicating that the observed values of T_{20-70} at all core distances seem not to be explained by any single model as in the case of lower primary energies(4). Since the showers observed in the present experiment were classified by their electron sizes, the sample of showers with a given electron size observed in the Akeno array contains showers initiated at the top of the atmosphere with a particular primary energy as well as those from lower primary energies starting at the deeper atmosphere. This fact was already confirmed from the measurement of atmospheric Cerenkov light at Akeno(3). Considering this fluctuation, a model with an enhanced $E^{1/2}$ multiplicity law reproduces the observed values of T_{20-70} better than a model with an $E^{1/2}$ multiplicity law at largest core distances.

4. Comparison of both arrival time distributions of muons above 0.5GeV and 1.0GeV

The average values of T_{20-70} for muons with energies above 0.5GeV are longer than those with energies above 1.0GeV by about 50% for showers with electron sizes in the range $10^{8.0}$ to $10^{8.5}$ and secθ in the range 1.0 to 1.2, as shown in figure 2. It is worth noting that the average values of T_{20-70} for muons above 0.5GeV are almost consistent with those above 0.42GeV obtained by the Nottingham group in the Haverah Park array(6), if the differences of the system time response and the threshold energy of muons in the two experiments are allowed for.

In figure 3 the mean arrival times of muons above 0.5GeV and those above 1.0GeV were calculated from observed muon signals and are compared with those estimated from the mean arrival times and lateral distributions of photoproduced and normal muons above 0.3GeV at sea level calculated by McComb et al[7] using a scaling model for proton and iron-initiated showers. After allowing for differences of the threshold energy of muons and the atmospheric depth between the calculation and the present experiment, we would conclude that the longitudinal development of muons in air showers with primary energies around 10^{18}eV is faster than that calculated by McComb et al using a scaling model and primary iron, furthermore the proportion of photoproduced muons to all muons above 0.5GeV must be much smaller than that calculated by these authors.

5. Discussion and conclusions

The observed values of T_{20-70} at small core distances are consistent with those calculated from low multiplicity models while at large core distances these observed values of T_{20-70} are well explained by high multiplicity models. According to the present calculation, the average production depth of muons arriving at the time intervals of T_{20-70} decreases with increasing core distance. We may conclude, therefore, that the longitudinal development of muons in air showers with primary energies in the range 10^{17}eV to 10^{18}eV is as fast as expected from an enhanced $E^{1/2}$ multiplicity law from 200gcm^{-2} to 500gcm^{-2} and is rather slow beyond that atmospheric depth. This conclusion is consistent with that derived from the arrival time distributions of muons in air showers with primary energies above 10^{17}eV observed at Chacaltaya[1] and of atmospheric Cerenkov light from air showers with primary energies in the range 5×10^{15}eV to 2×10^{17}eV observed at Akeno[3] as well as at Chacaltaya[2].

The fact that photoproduced muons appear to make no significant contribution to the arrival time distributions of muons with energies above 0.5GeV means that the character of particle interactions may be conveniently studied by measuring the arrival time distributions of muons above 0.5GeV, instead of 1.0GeV, and comparing them with calculations for normal muons. This way is important to reduce the cost of the shielding material of muon stations with large area in a large air-shower array.

References

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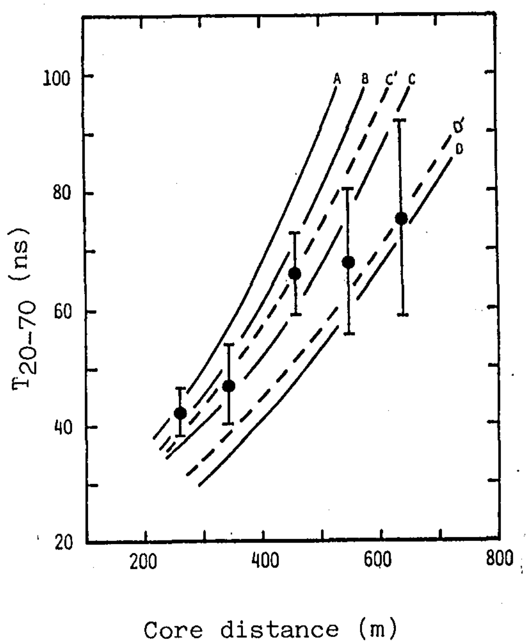

Figure 1. The average T_{20-70} of the arrival time distributions of muons with energies above 1.0GeV for showers with N_e of $10^{8.0}$–$10^{8.5}$ and secθ of 1.0-1.2 compared with those calculated from A: scaling model, B: a model with an $E^{1/4}$ multiplicity law, C: a model with an $E^{1/2}$ multiplicity law and D: a model with an enhanced $E^{1/2}$ multiplicity law and with first-interaction depths of 40gcm^{-2} for A-D and 120gcm^{-2} for C'-D'.

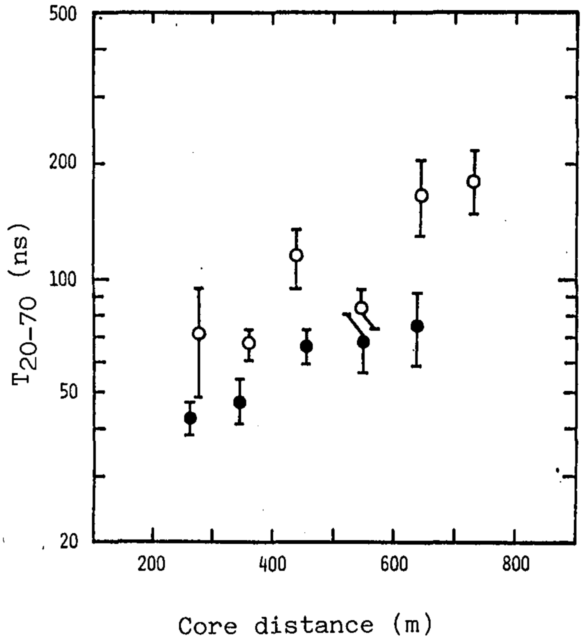

Figure 2. The average T_{20-70} of the arrival time distributions of muons with energies above 0.5GeV (○) and those above 1.0GeV(●).

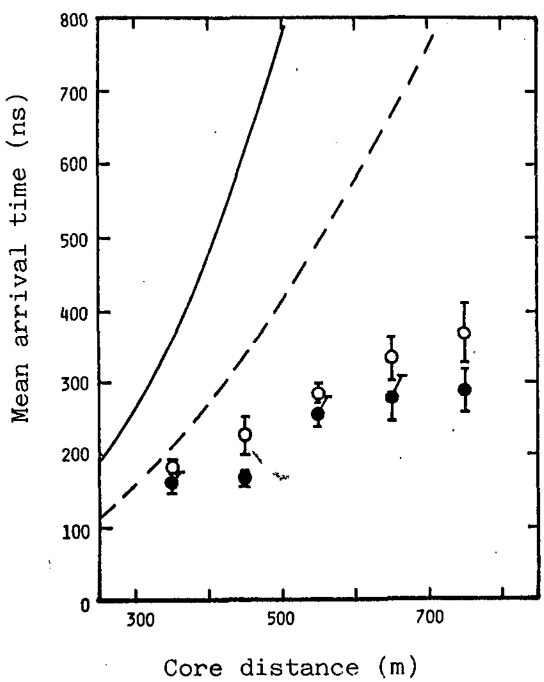

Figure 3. Mean arrival times of muons with energies above 0.5GeV (○) and those above 1.0GeV(●) for showers with N_e of $10^{8.0}$–$10^{8.5}$ and secθ of 1.0-1.2 against core distances compared with those of muons above 0.3GeV estimated for primary protons (———) and for primary irons (- - -) with energies of 10^{18}eV and secθ of 1.0.