Arrival time distributions of electrons in air showers with primary energies above 10^{18} eV observed at 900m above sea level

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1. Introduction

Detection of air showers with primary energies above 10^{19} eV with enough statistics is extremely important in an astrophysical aspect related to the Greisen cut off and the origin of such high energy cosmic rays. Recently, Linsley proposed a method to observe such giant air showers by measuring the arrival time distributions of air-shower particles at large core distances with a mini array[1].

We started experiments to measure the arrival time distributions of muons in 1981 and those of electrons in early 1983 in the Akeno air-shower array (930 gcm^{-2} atmospheric depth, 900m above sea level). During our observation, the detection area of the Akeno array was expanded from 1km^2 to 4km^2 in 1982[2] and to 20km in 1984 . Now the arrival time distributions of electrons and muons can be measured for showers with primary energies above 10^{19} eV at large core distances.

In this paper, the possibility of Linsley's proposal is examined on the basis of the arrival time distributions of particles measured with unshielded scintillation detectors for following three points:
(1) Is the time dispersion as proposed by Linsley a stuitable parameter?
(2) How large area is needed for the detector?
(3) Are core distances and shower sizes determined accurately enough?

Also reported in this paper are signals delayed by longer than 1μs from the shower front, together with a discussion on the nature of these signals.

2. Experimental

In the first run from January 1983 to October 1984, the arrival time distributions of air-shower particles was measured using a 4m^2 unshielded scintillation detector with a 5in fast photomultiplier (Hamamatsu Photonics R1250) located above both the M4 and ME3 muon stations in the Akeno array. Details of the measurement are described in the preceding paper[4] (hereafter called paper I).

Since the detection area of the Akeno array was expanded from 4km^2 to 20km^2 in October 1984[3], the scintillation detectors located at the M4 and ME3 muon stations were rearranged. In this second run four 4m^2 unshielded scintillation detectors were installed near the center of this new 20km^2 array and two 4m^2 scintillation detectors were located above the M4 muon station, separated by about 2km from the center of the new array. The added signal from these detectors was stored in the waveform

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recorder (Biomation 8100) with a sampling interval of 50ns in each station, when the local trigger pulse generated by a passage of at least one particle through any one of the detectors was coincident with a master pulse from the array to observe air showers with electron sizes larger than $10^{8.0}$.

The time response of the whole system in the first run was 39ns for rise time between 20% and 70% of the integrated full signal (T_{20-70}), while this value in the second run became larger due to the larger sampling interval of the recorder but this is not serious for observation of the arrival time distributions of particles at large core distances.

3. Arrival time distributions of particles at large core distances

On the basis of the observed arrival time distributions, the time dispersion (σ) proposed by Linsley as well as the rise time (T_{20-70}) were calculated for each shower. Average values both of σ and T_{20-70} are plotted against core distances in figure 1(a) and (b), respectively, for air showers with electron sizes from $10^{8.0}$ to $10^{8.5}$ and secθ from 1.0 to 1.2 in the first run. Also shown in figure 1(a) is the value of σ given by Linsley's empirical formula. Although the average values of σ obtained at core distances smaller than 500m are larger than the value of σ by Linsley, those at large core distances are consistent with each other. As is seen in figure 1(b) average values of T_{20-70} show a steeper dependence on the core distance than those of σ.

Though the sample of showers is limited at present, time dispersions for showers with electron sizes above $10^{9.0}$ observed in the two runs are plotted against core distances in figure 2. A large fluctuation in σ is seen at given core distances. The distribution of σ depends upon the number of observed particles. For a sample of showers with electron sizes of $10^{8.0}$-$10^{8.5}$ at core distances of 500-600m, the standard deviation of σ is 100ns for more than 10 particles while 30ns for more than 30 particles.

4. Signals delayed by longer than 1μsec

Signals, which correspond to the passage of more than 0.5 particles, delayed by longer than 1μs from the shower front have been seen in 15% of arrival time distributions measured for showers with electron sizes larger than $10^{8.0}$. Figure 3 shows the delay time distribution for air showers with electron sizes from $10^{8.0}$ to $10^{8.5}$ and secθ from 1.0 to 1.2. The frequency decreases monotonously up to 4μs with delay time while, after that time, this frequency is almost constant up to 10μs. The frequency of accidental signals is as low as $8 \times 10^{-4} (4m^2 \cdot 1\mu s)^{-1}$. Moreover, during first run, we observed five interesting showers in which one or successive delayed signals appeared in both the arrival time distribution of muons and that of electrons with almost same delay times, one of which is shown in figure 4(a), and observed one shower in which four successive delayed signals appeared in both arrival time distributions of electrons with almost same delay times at the M4 and ME3 muon stations separated by 100m from each other, which is shown in figure 4(b).

5. Discussion and conclusion

From the fluctuation in the time dispersions (σ) shown in figure 2, we may tentatively argue that the core distance and the shower size would be determined within an accuracy of 100-150m and $^{+120}_{-70}$%, respectively, if the number of particles observed in the detectors exceeds ten and the core

distance is around 1.5km. However, it should be mentioned from the
present analysis that the value of time dispersion (σ) is more sensitive
to the existence of delayed particles than that of T_{20-70} and the values
of T_{20-70} show a steeper dependence on core distance than that of σ.
Needless to say, it is most importnat to accumulate the sample of showers
and examine further the dependence of the dispersion on the electron size
and the zenith angle to make a final conclusion on the possibility of the
proposal made by Linsley.

The delayed signals observed in the present experiment seem to be
explained qualitatively as originated from low-energy neutrons which made
interactions in the scintillator. However, the successive delayed sig-
nals as described at the end of §4 look very interesting and more samples
should be necessary to clarify their origin.

References
(1) J. Linsley: Research Reports UNML-6/11/83, UNML-6/15/83 and UNML-6/
    20/83(1983)
(2) T. Hara et al: Proc. of 18th ICRC, Bangalore, 11(1983)276.
(3) M. Teshima et al: OG 9.4-8 in this Conference.
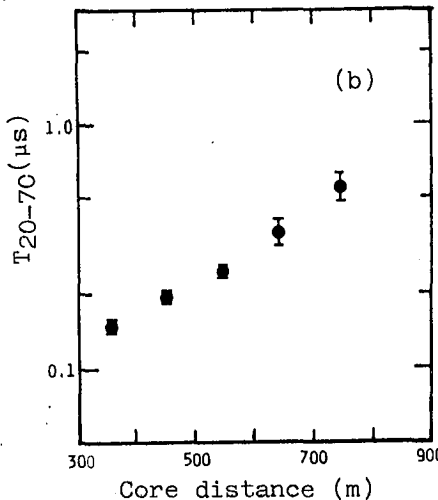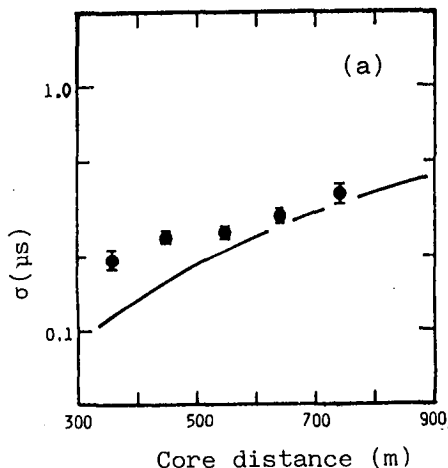(4) F. Kakimoto et al: HE 4.7-4 in this Conference.

Figure 1. The average σ (a) and T_{20-70}(b) of the arrival time distributions of particles in the first run for showers with electron sizes from $10^{8.0}$ to $10^{8.5}$ and $\sec\theta$ from 1.0 to 1.2. A curve in (a) is given by Linsley's empirical formula ($\sigma(ns)=2.6(1+R/30m)^{1.5}$, R:core distance)
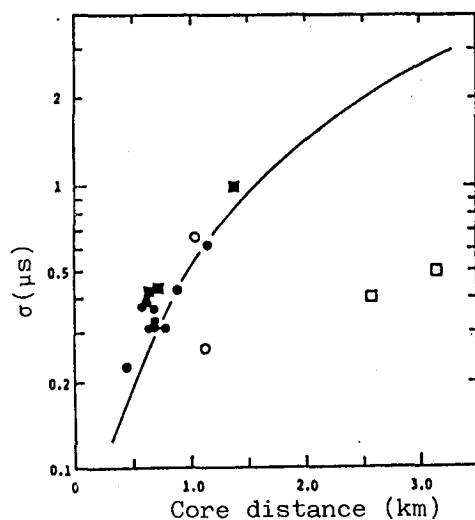

Figure 2. Time dispersions (σ) of the arrival time distributions of particles for showers with electron sizes above $10^{9.0}$ observed in the first run($\bullet$,o) and in the second run($\blacksquare$,$\square$). The number of particles observed in the unshielded detectors: $\geq$10 for $\bullet$ and $\blacksquare$; <10 for o and $\square$. Time intervals in the arrival time distributions of particles, within which time dispersions were calculated; 2.4µs for $\bullet$ and o; 10µs for $\blacksquare$ and $\square$. A curve is given by Linsley's formula.

/shower·4m^2

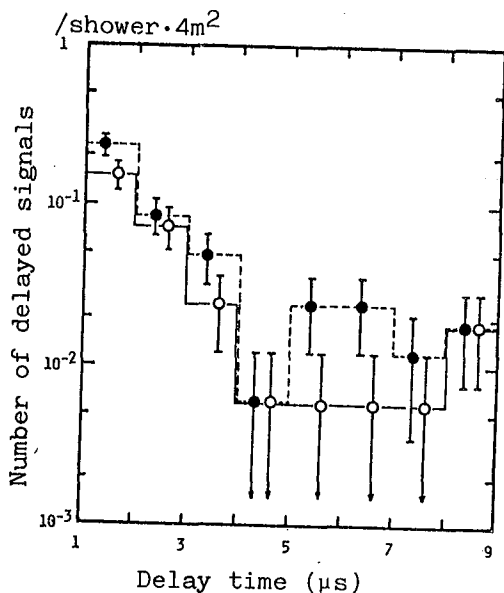**Figure 3.** Delay time distribution of signals delayed by longer than 1.0µs observed in the arrival time distributions of particles for air showers with electron sizes from $10^{8.0}$ to $10^{8.5}$ and secθ from 1.0 to 1.2. ●: more than 0.5 particles; ○: more than 1.0 particle.

Figure 4(a). Delayed signals observed both in the shielded detectors (①: t_d=0.76, n_d=14.8; ②: t_d=1.18, n_d=15.7) and in the unshielded detector (①': t_d=0.70, n_d=2.6; ②': t_d=1.12, n_d=3.2) at ME3 station for air shower with N_e of 3.7×10^8, θ of 15.2° and R of 327.3m. t_d: delay time in µs and n_d: the number of delayed particles. Time between both signals from the shielded detectors and the unshielded one is 1.8µs as described in paper I. Under-shoot in the figure is due to overloading in the amplifier of the recorder.

(b). Delayed signals observed in the unshielded detector both at M4 station (①: t_d=1.48, n_d=2.3; ②: t_d=2.00, n_d=2.4; ③: t_d=3.16, n_d=1.7; ④: t_d=3.56, n_d=2.0) and ME3 station (①': t_d=1.56, n_d=1.5; ②': t_d=2.04, n_d=0.9; ③': t_d=3.00, n_d=1.6; ④': t_d=3.76, n_d=4.4) for air shower with N_e of 2.8×10^9, θ of 8.1° and R of 697.3m from M4 and of 665.6m from ME3.