The longitudinal particle distribution in the extensive air shower disc

1975 J. Phys. A: Math. Gen. 8 997

(http://iopscience.iop.org/0305-4470/8/6/016)

J. Phys. A: Math. Gen., Vol. 8, No. 6, 1975. Printed in Great Britain. © 1975

The longitudinal particle distribution in the extensive air shower disc

C P Woidneck and E Böhm

Institut für Reine und Angewandte Kernphysik, Universität Kiel, Kiel, West Germany

Received 3 December 1974

Abstract. The longitudinal structure of the air shower particles in the shower disc has been investigated using the Kiel air shower array with additional fast-timing equipment. From the time delay measurements the longitudinal density distribution of particles has been derived, which near to the shower core ($r < 10\,\mathrm{m}$) can be described by $d(t) = 0{\cdot}39t^{0{\cdot}9}\,\mathrm{e}^{-0{\cdot}6t}$. This distribution proves to be similar to the longitudinal dispersion calculated for purely electromagnetic cascades.

1. Introduction

Extensive air shower (EAS) particles move nearly in the direction of the primary particle with velocities close to the velocity of light. Transverse momenta and scattering lead to a slightly different direction for each of the particles and cause a lateral dispersion; in addition a longitudinal dispersion is produced by the path length and velocity differences of the particles. So the shower particles are concentrated in a disc with a longitudinal and a lateral structure. The lateral particle distribution is rather well known and is widely used in routine air shower data analysis. Information on the longitudinal distribution is rather scant, especially concerning its detailed shape, but enough is known about it for the main application: the arrival direction measurement in showers.

The first experimental information on the thickness of the shower disc was given by Bassi *et al* (1953): from time delay measurements between shower particles they derived a disc thickness equivalent to 4–8 ns and a curvature of the shower front with a radius of more than 1300 m. The penetrating particles were found in a less curved disc of 8 ns thickness which lags the electrons by not more than 10 ns. This picture in its main features is still valid now, but has been improved in some respects. Linsley and Scarsi (1962) and Thielert and Wiedecke (1964) studied the lateral dependence of the disc thickness. Investigations of the disc of the hadron component were reported by Chatterjee *et al* (1965), and of the disc of the penetrating component, eg by Baxter *et al* (1968) and Armitage *et al* (1971). Hochart *et al* (1969) and Woidneck *et al* (1971) measured the curvature of the electron disc for core distances less than 100 m.

In all experiments quoted, only the arrival time of the first particles passing through the detectors has been measured. This method is not able to give details about the shape of the distribution of the shower particles in the disc. The aim of the present investigation has been to measure the shape of the particle disc. The longitudinal distributions of electrons and of muons have been scanned for core distances $r < 100\,\mathrm{m}$ and for time delays of up to 30 ns with respect to the shower front.

2. Apparatus and method

An array of sixteen 1 m^2 scintillation counters provides basic information on the shower, ie core location, size and arrival direction (Bagge *et al* 1965). Three fast-timing scintillation counters of different area have been added to measure the longitudinal distribution of the shower particles. Two unshielded detectors of 1 m^2(SC1) and 0·01 m^2(SC2) area and a shielded one of 1 m^2(SC3) have been used (figures 1 and 2). The large unshielded detector is triggered by the first of many particles passing and indicates

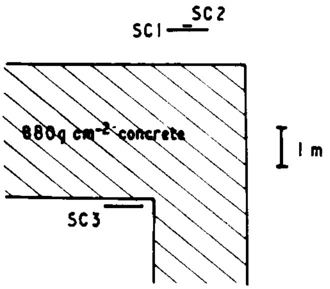
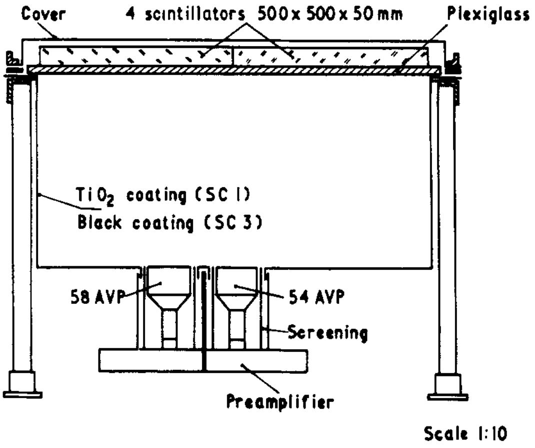
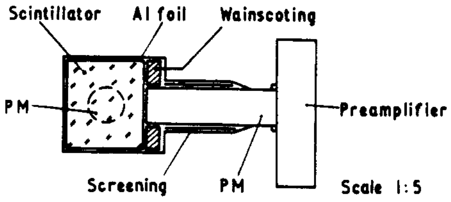


Figure 1. Arrangement of the fast-timing counters.



Scintillation counter (1m²)



Scintillation counter SC2 (10x10x8cm³)

Figure 2. Construction of the fast-timing counters.

the arrival of the shower front. By selecting single particle traversals through the small detector the arrival time of single particles with respect to the shower front can be determined. In this way it is possible to scan the shower disc rather directly. By sampling many showers one obtains the average longitudinal structure of the disc. The same method can be applied to the shielded detector (880 g cm^{-2} of concrete). All detectors consist of plastic scintillators with two multipliers, one of which (53 AVP, 54 AVP) is employed to record the number of particles passing the scintillator, the other one (56 AVP, 58 AVP) to measure the arrival time.

The error in the time measurement has been derived from prompt coincidences of both counters in question, using local showers with rather small longitudinal dispersion and single particle traversals in SC2, SC3. The time resolution (standard deviation) of the arrangement depends on the amount of light on the photomultiplier of SC1 and reaches a constant value of $\sigma = 1{\cdot}3$ ns for the system SC1/SC2 at a pulse height equivalent to 10 particles m^{-2}. The corresponding value for the system SC1/SC3 is $\sigma = 2{\cdot}7$ ns. The detection efficiency of the timing channels is 0·99 and 0·91 respectively.

3. Results

With the detectors SC1, SC2 and SC3 the following data have been obtained.

(i) Arrival time differences between a single particle in SC2 and many particles in SC1. As mentioned in § 2 the longitudinal distribution of air shower particles is probed in a rather direct manner.

(ii) Arrival time differences between a single particle in SC3 and many particles in SC1, providing information on the longitudinal distribution of muons.

(iii) Arrival time differences between single particles in SC2 and SC3. To some extent the mean value of the resulting distributions represents the delay between the electron and the muon disc. From the lateral dependence of this delay one can deduce the curvature of the electron disc. The result of this analysis has already been reported (Woidneck *et al* 1971). In the present paper we are only concerned with (i) and (ii).

3.1. The electron disc

The data recorded in (i) have been subdivided according to core distance r (0–4–10–25–63 m) and number of particles ρ_1 in SC1 (this procedure is suggested by the expected lateral dependence of the disc structure and by the intrinsic influence of ρ_1 on the time delay).

Typical arrival time distributions are shown in figure 3. They are not symmetrical: there is a fast rise, a maximum at a few nanoseconds and a slow decrease up to the maximum detectable time delay of $t_{\max} = 30$ ns. For fixed r there is a remarkable dependence on ρ_1. Near to the shower core (4–10 m) and for densities $10\ m^{-2} < \rho_1 < 100\ m^{-2}$ this is mainly an instrumental effect: the time of detection of the particle is a function of the density because of the finite rise time of the photomultiplier pulse and the discrimination method used (leading edge). The response to time is shifted with ρ_1 as indicated (events with $t < 0$ are due to the finite resolution of the detection system $\sigma = 1{\cdot}3$ ns). At larger core distances ($r > 25$ m) the dependence of the arrival time on ρ_1 is still stronger. This is due to additional delays caused by the muon component as explained later in § 3.2. There exist events with particles delayed by 30 ns $< t <$ 1 μs without exact arrival time determination. Some of them are due to the finite detection efficiency of 0·99. In total

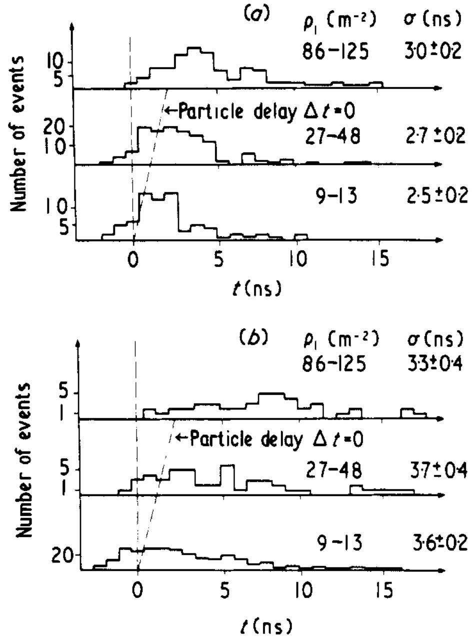


Figure 3. Single particle arrival time distribution. (*a*) 4 m $\leqslant r <$ 10 m; (*b*) 25 m $\leqslant r <$ 63 m.

209 (3·4 %) 'delayed' particles have been found, becoming more frequent with increasing core distance: 1·5 ± 0·04 % at 4–10m, 8·9 ± 1·3 % for $r > 63$ m.

A longitudinal particle density distribution function has been derived from the measured arrival time differences. The function $d(t) = t^a \exp(-bt)$ with parameters a and b has been chosen to be fitted to the measured arrival time distribution at core distances 4–10 m, allowing for the finite time resolution of the detection system. The result is shown in figure 4. Apparently the longitudinal distribution of shower particles can be described by the parameters $a = 0{\cdot}9 \pm 0{\cdot}3$, $b = 0{\cdot}6 \pm 0{\cdot}1$ ns^{-1} up to $t = 12$ ns. The observed flat tail, however, exceeding 12 ns (4·4 % of the events) is not reproduced correctly by this function.

The time delay distribution at larger core distances is different from the distribution near to the core. This change can be explained by a larger contribution of muons which arrive earlier than the electrons (see Woidneck *et al* 1971). This extreme (muon-) shower front is not always recognized by SC1, but is detected more frequently with increasing particle density or core distance and thus number of muons. The measured distributions are superpositions of time measurements with respect to two different fronts, the muon front or the electron front. The electron disc has been derived assuming a muon disc $d(t)$ with $a = 1$, $b = 2$, which is suggested from the arrival time distribution of penetrating particles described in § 3.2, preceding the electrons by a time of 6 ns taken from Woidneck *et al* (1971). A best fit leads to a disc structure for the electron component described by parameters $a = 0{\cdot}3 \pm 0{\cdot}3$, $b = 0{\cdot}4 \pm 0{\cdot}1$ ns^{-1}. However this result is not as reliable as the one obtained at small core distances.

3.2. The muon disc

The measurements of penetrating particles (mainly muons, $E \geqslant 2$ GeV) have been

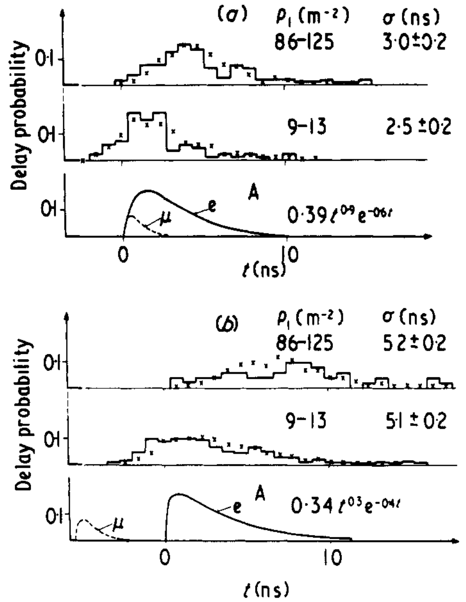


Figure 4. Comparison of measured and assumed trial distributions. The crosses are results expected from the density distributions. The curves marked A are those described by the parameters a and b in the relation $t^a \exp(-bt)$ for the values of a and b shown.
(*a*) $4\,\text{m} \leqslant r < 10\,\text{m}$; (*b*) $25\,\text{m} \leqslant r < 63\,\text{m}$.

analysed in a similar way to those of the electrons. Some typical arrival time distributions are shown in figure 5. It is to be seen, that the time delay distribution does not alter noticeably with core distance. The standard deviations are constant within experimental errors. Taking the symmetrical part of the distribution, ie cutting off the tail, the corresponding standard deviation is equal to the time resolution. Thus in first approximation the longitudinal density of penetrating particles can be supposed to be a spike at the shower front with a flat part up to 15 ns at least.

4. Discussion

For an interpretation of the experimental results a comparison with a three-dimensional shower simulation would be most suitable. This simulation should pay regard to the following effects, which are of differing importance for the various kinds of particles and core distances (cf Blake and Harris 1970): a time delay is produced by path length differences due to

(*a*) transverse momenta of the particles;
(*b*) multiple scattering;
(*c*) geomagnetic deflection; and by
(*d*) differences in particle velocities.

Calculations of this type are not yet available. For purely electromagnetic showers a computation has been performed by Locci *et al* (1967) considering effects (*a*), (*b*) and (*c*). Vertical showers originating from γ rays of energy 10^{12}, 10^{13} eV at a height of 15 km above sea level have been simulated. The calculations provide the longitudinal electron

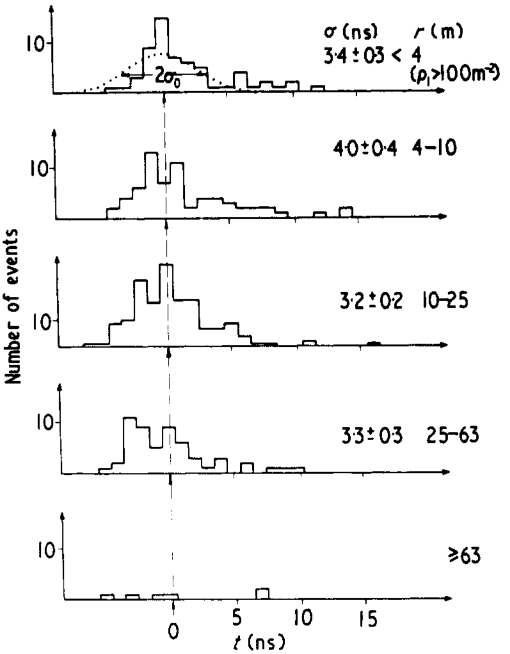


Figure 5. Arrival time distribution of single penetrating particles ($E_\mu \geq 2$ GeV).

density at various observation levels and core distances. The distributions change only slightly with energy or observation level at core distances larger than 10 m. Thus their results could be valid for even higher energies at sea level. A comparison with our measurements (figure 6) shows rather similar behaviour. As far as the longitudinal

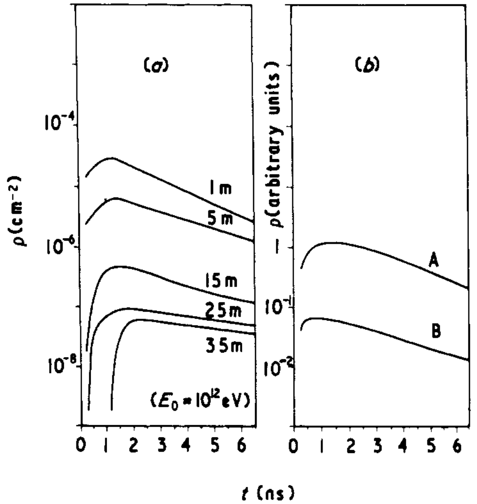


Figure 6. Comparison of longitudinal electron density distributions. (*a*) Calculated by Locci *et al* (1967); (*b*) present experiment: curve A, $c_1 t^{0.9} \mathrm{e}^{-0.6t}$, 4 m $\leq r <$ 10 m; curve B, $c_2 t^{0.3} \mathrm{e}^{-0.4t}$, 25 m $\leq r <$ 63 m.

dispersion of shower particles is concerned, there seems to be no difference between purely electromagnetic cascades and showers produced by hadrons, confirming that the main contribution to the delay comes from the electromagnetic component due to scattering.

As pointed out by Lapikens *et al* (1973) the arrival time distribution of shower particles contains information about the longitudinal shower development. At small core distances $r < 60$ m this does not seem to be the case; the delay is mainly due to Coulomb scattering and not caused by path length differences due to the transverse momentum distribution as at large core distances.

Comparing the longitudinal distribution functions at the two core distance intervals 4–10 m, 25–63 m there seems to be no change in the mean delay $\bar{t} = (a+1)/b$: 3·2 and 3·3 ns respectively, while there is a slight increase in the standard deviation $\sigma = [(a+1)/b^2]^{1/2}$: 2·3 and 2·9 ns respectively. This change is not as fast as could be expected from the dependence of the mean electron energy on core distance (Vernov *et al* 1960, Fukui *et al* 1960, Holtrup 1972). We conclude that the disc width does not depend on the mean particle energy, which changes strongly near to the core ($r < 10$ m); consequently a change in shower age and the related change in mean particle energy will not be observable by disc structure measurements, at least on the average. But before drawing final conclusions it would be useful to measure the disc structure in individual showers and the fluctuations in disc structure. To do that other methods than the one used here have to be developed.

5. Application

In recent years some shower phenomena have been investigated which depend strongly on the structure of the shower particle disc: the time distribution of Cerenkov light (Bosia *et al* 1973) and the radio wave spectrum from the shower particles produced in the atmosphere (eg Allan 1971). In calculations of the radio wave frequency spectrum assumptions on the disc structure have been used: Fujii and Nishimura (1971) adopted $d(t) \sim t^{s/2-1}$, derived from the shower calculations by Nishimura; the treatment by Allan (1971) is equivalent to a similar type of distribution.

The contribution of the time delay distribution of particles to the radio frequency depends on the Fourier transform of the structure of the disc at the atmospheric depth of emission. The contribution to the response of a receiver is the integral effect of particle number and disc structure at the different stages of development. The longitudinal distribution functions $d_1 \sim t^{-\kappa}$ and $d_2 \sim t^a \exp(-bt)$ lead to frequency spectra $f_1(\nu) \sim \nu^{\kappa-1}$ and $f_2(\nu) \sim (b^2+\nu^2)^{-(a+1)/2}$ respectively, both giving a power law spectrum at high frequencies, $\nu^{\kappa-1}$, $\nu^{-(a+1)}$ but differing at smaller frequencies ($\nu < b$) (for experimental values of b see § 3.1).

The spectrum f_2 does not agree with the spectrum of radio waves observed experimentally (eg Allan 1971). Qualitatively f_2 shows the same trend as given by the calculations of Hough (1973), a shift of the maximum of the frequency distribution to smaller values with increasing core distance. But the flattening of f_2 starts at too high frequencies. Since it seems not reasonable to adopt a much smaller value of b for the disc structure of particles the main contribution to the radio wave spectrum should not come from the shower disc but from other types of path length differences of the interfering waves.

Acknowledgments

The authors are grateful to Professor E Bagge for his encouragement. They wish to thank Professor J Trümper (now at Tübingen University, West Germany) for valuable discussions.

References

Allan H R 1971 *Progress in Elementary Particle and Cosmic Ray Physics* vol 10 (Amsterdam: North-Holland) pp 171–296

Armitage M, Blake P R, Fergeson H, Nash W F and Thomas D W E 1971 *Proc. 12th Int. Conf. on Cosmic Rays, Hobart* vol 3 (Hobart: University of Tasmania) pp 1068–73

Bagge, E, Böhm E, Fritze R, Roose U J, Samorski M, Schnier C, Staubert R, Thielheim K O, Trümper J, Wiedecke L and Wolter W 1965 *Proc. 9th Int. Conf. on Cosmic Rays, London* vol 2 (London: The Institute of Physics and The Physical Society) pp 738–41

Bassi P, Clark G and Rossi B 1953 *Phys. Rev.* **92** 441–51

Baxter A J, Watson A A and Wilson J G 1968 *Can. J. Phys.* **46** S9–12

Blake P R and Harris D M 1970 *Acta Phys. Hung.* **29** *Suppl.* 3 633–7

Bosia G, Navarra G, Saavedra O, Böhm E and Cachon A 1973 *Proc. 13th Int. Conf. on Cosmic Rays, Denver* (Denver: University of Denver) pp 2375–7

Chatterjee B K, Murphy G T, Naranan S, Sreekantan B V, Srinivasa Rao M V and Tonwar S C 1965 *Proc. 9th Int. Conf. on Cosmic Rays, London* vol 2 (London: The Institute of Physics and The Physical Society) pp 802–4

Fujii M and Nishimura J 1971 *Proc. 12th Int. Conf. on Cosmic Rays, Hobart* (Hobart: University of Tasmania) pp 2753–6

Fukui S, Hasegawa H, Matano T, Miura I, Oda M, Suga K, Tanahashi G and Tanaka Y 1960 *Prog. Theor. Phys., Suppl.* **16** 1–53

Hochart J P, Maze R, Catz P and Gawin J 1970 *Acta Phys. Hung.* **29** *Suppl.* 3 689–93

Holtrup G 1972 *Dipl. Thesis* Kiel University

Hough J H 1973 *J. Phys.* A: *Math., Nucl. Gen* **6** 892–900

Lapikens J, Watson A A, Wild P and Wilson J G 1973 *Proc. 13th Int. Conf. on Cosmic Rays, Denver* (Denver: University of Denver) pp 2582–7

Linsley J and Scarsi L 1962 *Phys. Rev.* **128** 2384–92

Locci M, Picchi P and Verri G 1967 *Nuovo Cim.* B **50** 384–8

Thielert R and Wiedecke L 1964 *Z. Phys.* **179** 199–212

Vernov S N, Goryunov N N, Dmitriev V A, Kulikov G V, Nachin Ju N, Solovieva V I, Strugalsky Z S and Khristiansen G B 1960 *Proc. 6th Int. Conf. on Cosmic Rays, Moscow* vol 2 (IUPAP) pp 109–14

Woidneck C P, Böhm E, Trümper J and de Villiers E J 1971 *Proc. 12th Int. Conf. on Cosmic Rays, Hobart* vol 3 (Hobart: University of Tasmania) pp 1038–42