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Fluctuation studies of large air showers: the composition of primary cosmic ray particles of energy $E_p \sim 10^{18}$ eV

A A Watson and J G Wilson

Department of Physics, University of Leeds, Leeds, LS2 9JT, UK

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Abstract. The time sequence of detection of Čerenkov light in the deep-water detectors used at Haverah Park is used to establish a shower parameter insensitive to the total energy of the primary particles but yielding a measure of fluctuations of development among showers. Values of departure of individual showers from the mean behaviour now established are most readily understood if some of the primary particles of energy $E_p \sim 10^{18}$ eV are light, probably protons but perhaps α particles.

1. Introduction

The time structure of incidence of extensive air showers on detectors has been remarkably little studied since the pioneering work of Bassi *et al* (1953), which demonstrated that it was possible to measure the direction of arrival of extensive air showers using an array of scintillators and fast timing techniques, and that the shower front close to the axis had a measurable thickness of several metres. At these distances the principal cause of shower front broadening is the difference in velocities of the particles produced along the shower axis, but at axial distances of a few hundred metres velocity and path length differences are compounded to create a shower front of a hundred metres or more in thickness. Because observations on the largest air showers ($>10^{17}$ eV) are usually made far from the axis, Linsley and Scarsi (1962a) undertook a detailed and systematic study of the time structure of the arrival of electrons and muons in the distance range $200 < r < 1500$ m, the major purpose of which was to identify the optimum method of determining shower directions. It is worth noting that this work also very clearly identifies the need for long integration times in the density measuring channels of EAS systems.

As well as recognizing the instrumental importance of shower front structure, both the Volcano Ranch and Haverah Park groups (Linsley and Scarsi 1962a, Wilson *et al* 1963) realized that a detailed study of the shower front might provide a possible method of yielding information on the longitudinal development of EAS. Earlier work at Haverah Park (Baxter *et al* 1968, Baxter 1969) has confirmed the Volcano Ranch work and demonstrated that large-area water-Čerenkov detectors can be exploited to study average features of EAS. In this paper we present a detailed account of some recent work in which the advantages of the large area (34 m^2) detectors of the Haverah Park 500 m array are used to study the time structure of shower fronts in individual showers at 2 or 3 widely spaced points in the shower plane. We demonstrate, without recourse to detailed shower model calculations, that fluctuations exist between showers which are greater than expected on the basis of measurement errors and statistical sampling effects alone. Using model calculations as guidelines, we show that it is likely that the observed fluctuations are most readily understood if the primary cosmic ray particles $E_p > 10^{18}$ eV include protons or α particles.

We think our conclusions at 10^{18} eV, although not yet quantitative, are more firmly based than other existing evidence on the nature of primary particles above 10^{17} eV. The work of Linsley and Scarsi (1962b) originally presented as evidence for a high proportion of protons in the flux above 10^{17} eV has recently been re-evaluated and held (Linsley 1973) to be consistent with a heavy composition. At similar energies Orford and Turver (1968) reported measurements on high energy muons at large axial distances as suggesting a primary flux of average mass greater than 10: from more refined model calculations by the same group, it now appears that muon momentum spectrum measurements are not capable of distinguishing between masses as disparate as 1 and 56! Using measurements of the muon lateral distribution function from primaries of 10^{17} eV–10^{18} eV, Armitage *et al* (1973a) have shown convincingly that certain Hillas models are improbable, but also that their data are, as yet, not sufficiently model selective to allow definite statements about primary masses unrelated to the model used. Kawaguchi *et al* (1971) proposed that the absence of fluctuations in muons observed at Chacaltaya (5000 m) combined with evidence for muon fluctuations in showers recorded at Tokyo from primary particles considered to be of the same energy, indicated a high proportion of protons at about 10^{18} eV. However, details of this work currently available are insufficient for critical evaluation.

A preliminary report of our measurements was given at the Denver cosmic ray conference (Lapikens *et al* 1973).

2. Outline of the method

The investigation which we have undertaken to identify and interpret shower-to-shower differences in the time structure of shower fronts has lead naturally to two modes of approach.

(i) Work possible with the existing shower records, so that use may be made of the data bank of showers which has been maintained at a high level of quality, and which contains several years of material; and (ii) work to be started with the development of a system of additional records established for this particular application.

The present paper is concerned entirely with the existing material in the data bank referred to in (i), and, further, with the records of the four large (34 m^2) detectors which form the central unit of the main shower array at a separation of 500 m.

Any one of these channels will, if energy is released nearly instantaneously in the detector, as it is for example when a small local shower falls with its core close to that detector, yield a record which is characteristic of the particular recording channel. (The bandwidths of the four channels in fact differ significantly.) If, however, the energy enters the detector over a finite time, as it does when a shower front several hundred metres from the axis passes through it, the recorded pulse is spread out and so becomes slower. For our purpose it is necessary to identify some measurable parameter of the shape of the pulses, and to determine whether differences characteristic of individual showers can be separated from other factors which modify the form of the recorded signals and from any inherent uncertainty in the actual process of measuring the chosen parameter.

2.1. The measurement parameter

For the present material a readily measurable parameter, not leading to complexities of interpretation, is needed: that chosen, and referred to in what follows as '$t_{1/2}$' is the time over which the recorded signal increases from 10 to 50% of its final amplitude. The lower, non-zero, point of measurement is selected because the actual time when the trace leaves the base line is often not readily determined to a precision at all comparable with what is possible at the chosen 10% level, while the upper limit is in fact derived from a series of measurements along the rising trace which are extended to 65–75% of full amplitude. Using an early shower development model (model A) due to Hillas *et al* (1970), the $t_{1/2}$ parameter follows the median point of the arrival time of water-Čerenkov light, $\bar{t}$, in our detectors closely, and for a proton primary would be closely related to the depth of first interaction†. More recently, Dixon and Turver (1974) have shown that the median arrival time of muons (> 1 GeV) is similarly strongly correlated with the depth of first interaction. We regard $t_{1/2}$ as a measurable parameter closely related to these computed significant quantities, although our interpretation of our work will, as far as possible, avoid dependence upon this relationship with particular model studies.

2.2. Interpretation of the measured parameter

The measured value of $t_{1/2}$ in a particular detector, and relative to its own characteristic instantaneous response, is expected to be a function of the radial distance of the sampling point from the shower axis, r, of the zenith angle of impact of the shower, θ, and perhaps of the primary total energy, E_p. The variation with r is relatively rapid and that with θ was not predictable at the time the work started. Regarding the variation with E_p, the effective spread of energy was at no stage of the work large, but a test that $t_{1/2}$ is insensitive to E_p is described below.

In addition to these general features of showers, an actual determination will involve the uncertainty of measurements on the oscilloscope record of each pulse, and, more importantly, the departure from average behaviour of the recorded pulse arising because detectors of limited area take from the shower front a finite sample which is subject to fluctuations. It is a necessary preliminary to make reliable estimates of these non-specific factors, and for this purpose a trial set of data (group A) was selected and $t_{1/2}$ determined.

Group A consisted of more than 400 showers (April 1971 to February 1972) with mean primary energy about 5×10^{17} eV, with zenith angle less than 40° and with at least two detectors yielding signals of greater than 0·8 equivalent muons m^{-2} (> 7 GeV energy deposition in a 34 m^2 detector) lying between 350 m and 600 m from the shower axis. All the 900+ pulses of this set were measured independently by both authors; the great majority of these measurements were in close accord, and of the remainder almost all were brought into similar agreement by a second pair of measurements. Some of these repeated measurements were from poor records which required exceptional care in measurement, but others stemmed from gross errors in transcription or in punching-in data for the computing process. The standard deviation of the reading error was found from the complete data of these pulses to be somewhat less than 6 ns, while there was virtually no systematic bias as between observers (~ 1 ns).

† We are grateful to Mr J Lapikens for this early information from studies which he has undertaken.

The data group A also allowed regression lines r against $t_{1/2}$ to be established for each of the four 34 m^2 detectors and for three zenith angle bands 0–20°, 20–30°, 30–40°, yielding expressions of the form $t_{1/2} = a+br$. In deriving the values shown in table 1, account is taken of the fact that all four channels must exhibit the similarity of form required by their common origin. A typical example of the data used is given in figure 1, which refers to detector 2, $\theta < 20°$.

Table 1. Regression lines of $t_{1/2}$ in the form $a+br$ (r in metres).

Detector	1	2	3	4
0–20°	$46+0{\cdot}19r$	$43+0{\cdot}20r$	$51+0{\cdot}19r$	$35+0{\cdot}20r$
20–30°	$48+0{\cdot}17r$	$45+0{\cdot}18r$	$55+0{\cdot}17r$	$37+0{\cdot}175r$
30–40°	$51+0{\cdot}15r$	$47{\cdot}5+0{\cdot}16r$	$56+0{\cdot}15r$	$40+0{\cdot}15r$

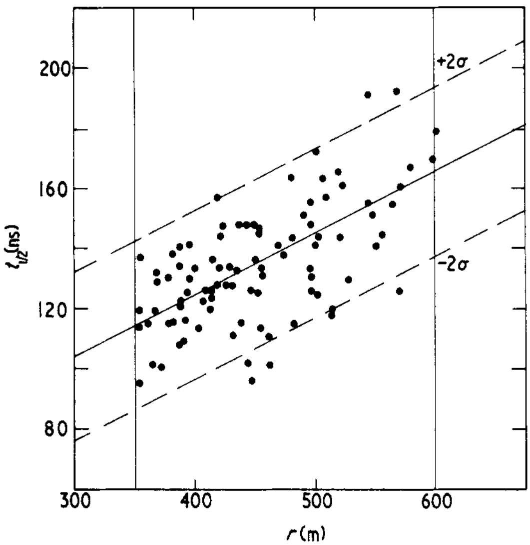

Figure 1. Measurements of the parameter '$t_{1/2}$' for a particular detector (number 2) and zenith angle range (<20°), shown as a regression line and the 2σ limits of the distribution. σ = 14 ns.

The values of a and b in table 1 have been derived from the group A data for which $E_p \sim 5\times10^{17}$ eV. A test of the insensitivity of these coefficients to E_p is provided if the deviations of the 225 $t_{1/2}$ measurements of group B (see § 2.4 below) from the regression lines so defined are determined. These measurements refer to showers of $E_p \sim 1{\cdot}5\times10^{18}$ eV, and the mean deviation of these 225 measurements from the 5×10^{17} eV regression lines is $0{\cdot}1\pm1{\cdot}1$ ns. Over the range of energy covered in this work, therefore, the insensitivity of $t_{1/2}$ to energy is adequately established.

2.3. *The sampling error*

At a signal intensity of 1 equivalent muon m^{-2}, the pulse at $r \sim 600$ m for vertical showers is derived in roughly equal proportions from about 15 muons and from several hundred low energy electrons and photons (<10 MeV) falling on the 34 m^2 detector. The sampling error is thus certainly not negligible, and it is apparent that significantly smaller detector areas would be unsuitable for an investigation along these lines.

While measurement errors are in principle controllable, and could if necessary be reduced, the variations associated with sampling are intrinsic functions of detector area and so of all large EAS measurements: they are the fluctuations which would be encountered were identical measurement procedures applied repetitively with a particular detector to a large number of macroscopically identical showers. Since sampling variations cannot be dissociated from measurement errors they cannot be measured independently: what can be measured is the combined effect of measurement and sampling.

An estimate of the combination of measurement error and sampling fluctuations was obtained from pairs of records within individual showers of the group A data in which r differs by less than 50 m for the two detectors yielding measurements of $t_{1/2}$. This procedure is adopted because it is independent of the accuracy of the regression line $t_{1/2}$ against r. Values based upon the six possible pairs of detector units and for θ less than and greater than 20° respectively are given in table 2.

Table 2. Average spread of $t_{1/2}$ between records in the same shower, Δr < 50 m.

	$\theta < 20°$		$20° < \theta < 40°$	
Detector pairs	Number of pairs measured	$\overline{\Delta t_{1/2}}$ ns	Number of pairs measured	$\overline{\Delta t_{1/2}}$ ns
1+2	27	13·6	42	17·3
1+3	18	20·1	41	16·3
1+4	34	15·7	45	22·6
2+3	17	18·4	37	14·1
2+4	9	19·5	29	20·0
3+4	15	25·2	42	18·1

The values in table 2 must certainly reflect to some extent also the differences of bandwidth of the particular pair of detectors, and with this in mind reference to table 1 suggests that the combinations least affected by such differences will be (1, 2), (2, 3). From these we derive the value:

$$\sigma_{ms} = (\sigma_m^2 + \sigma_s^2)^{1/2} = (13{\cdot}9 \pm 1{\cdot}2)\ \text{ns},$$

where σ_{ms} is the standard deviation of the combined effect of measurement and sampling; σ_m and σ_s refer to the uncertainties introduced by measurement and sampling effects independently. This value shows that for 34 m^2 detectors within the distance and zenith angle ranges used here and for signals greater than 0·8 m^{-2}, sampling fluctuations are significantly more important than are errors in the measurement process. We have not, it will be noted, excluded the possibility that some part of this effect might not arise from large-scale irregularities of shower development which could hardly be described as 'sampling fluctuations', but we have encountered no indication that such differences happen at great distances from shower axes.

2.4. *Shower-sensitive data*

The orders of magnitude established above give an indication of a satisfactory procedure for establishing the presence or otherwise of shower-to-shower variations of $t_{1/2}$. Indeed the simple test of comparing the sums and differences of two signals for each shower from the appropriate regression line provides *prima facie* evidence that such a variation exists (Lapikens *et al* 1973).

Following this indication the second sample, 'group B', was established involving very much more stringent criteria. In this sample, *three* signals within the range 350–600 m and in showers with $\theta < 40°$ were required at the rather high minimum density of 1·5 equivalent muons m^{-2} ($\sim$ 12 GeV energy deposition in each detector). Here the sampling error may be anticipated to be reduced, since higher signals are required, while the fact that three independent samples were taken in different parts of each shower, hundreds of metres apart, emphasizes that what is derived is a non-local shower property. This selection identifies showers from a rather narrow energy band around $1{\cdot}5 \times 10^{18}$ eV. Three pulses meeting these criteria for each of 75 showers recorded between April 1971 and July 1973 were measured, and figure 2 shows the average distance in time of the

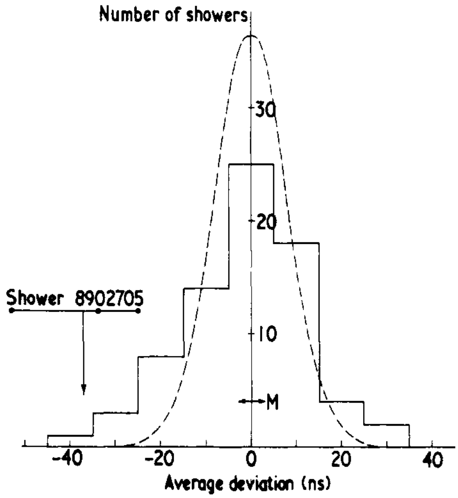

Figure 2. Group B data, showing the distribution of the average difference from the respective regression lines of the three measurements on each of 75 showers. Negative values refer to the slow averages. The broken curve shows the expected distribution were all measurements independent and exhibiting the measurement and sampling variation of the extensive group A data, $14/\sqrt{3}$ ns. The arrow M shows the standard deviation of error to be assigned to accuracy of measurement only.

The three points on the left and their average, shower 8902705, refer to the extreme shower discussed in the text and illustrated in figure 3.

mean of each set of three from the appropriate regression line. Were these to form an unrelated sample from showers of identical development and with measurement errors and sampling fluctuations similar to those determined for group A, these sets would be expected to form a gaussian distribution about the regression lines of standard deviation about $14/\sqrt{3} \sim 8$ ns. The distribution is seen to be broader than even this figure would indicate, but since the general quality of this material is higher than that of group A, and the average densities greater, the actual measurement and sampling uncertainty may be rather narrower than is indicated here.

2.5. Significance of samples in group B and also in group A

While figure 2 gives visually convincing evidence that shower-characteristic features are present in the pulse measurements described above, it is useful to make a formal estimate of the weight of evidence in this material, and for this purpose an analysis of variance is used.

The data consist of a number of samples (showers) each containing three (or, for much group A data, two) items (rise-time deviations). If the samples were derived at random from a perfectly homogeneous population, the variation between sample averages would be commensurate with the population variance as indicated by the variation within individual samples. Departure from a null result indicates that, as well as a 'within-sample' variance there is a 'between-sample' variance. 'Within-sample' and 'between-sample' variances can be compared using Snedecor's F-test if the number of samples is small, or using the 'error of difference' method if the number of samples is large.

The results of an analysis of variance for the data described above using both approaches are given in table 3. Both for the large group A sample and for the more

Table 3. Analysis of variance.

Shower set	Group B: 75 showers, 3 measured pulses, $\Delta > 1{\cdot}5\ \mathrm{m}^{-2}$ in each	Group A: 432 showers, 2 or 3 measured pulses, $\Delta > 0{\cdot}8\ \mathrm{m}^{-2}$ in each (excluding showers meeting group B criteria)
Between-shower variance σ_1^2 (ns^2)	518	290
Number of degrees of freedom ν_1	74	431
Within-shower variance σ_2^2 (ns^2)	216	218
Number of degrees of freedom ν_2	150	531
$F = \sigma_1^2/\sigma_2^2$	2·38	1·32
$\dfrac{\sigma_1 - \sigma_2}{\text{Standard error of difference}}$	4·47	3·11
Probability of null hypothesis	$\sim 4 \times 10^{-6}$	$\sim 0{\cdot}01$
σ_f (see § 3.2)	$(9{\cdot}9 \pm 1{\cdot}8)$ ns	$(5{\cdot}8 \pm 1{\cdot}3)$ ns
Average E_p	$1{\cdot}5 \times 10^{18}$ eV	5×10^{17} eV
Average r (metres from axis)	465 m	435 m

stringently defined but smaller group B sample there is a strongly significant non-null result in the direction which is physically reasonable. The probability that the whole result can be a chance occurrence is of the order of 10^{-6}.

It should be noted that the 'within shower' variances lead to an estimate of 14·7 ± 0·5 ns as the standard deviation, σ_{ms}, of the combined effect of measurement and sampling. This is in agreement with the value derived in § 2.3 by a method which was independent of the regression lines.

3. Variations of $t_{1/2}$ and shower structure

The data presented above prompt three lines of further consideration: (i) the extent to which the average values of $t_{1/2}$ described in table 1, and for which one group of data is illustrated in figure 1 are in accord with other experimental observations and with the predictions of model studies; (ii) the conclusion which can be derived from the overall shower-to-shower variations established in table 3; and (iii) the interpretation of the extreme variations involving large $t_{1/2}$ (that is, slow signal) occurring in group B data.

3.1. Average values of $t_{1/2}$

Calculations by Baxter (1969) give details of the expected time distribution of muon and soft-component signals for a shower of average development initiated by a proton of energy about 10^{17} eV. An important conclusion is that the soft-component signal is delayed with respect to that of muons to the extent that, in the distance range 400–600 m, approximately 40% of the muon signal has arrived before even 10% of that initiated by the soft component. This particular figure has not been experimentally tested, nor has the work been extended over a variety of interaction models.

For this same distance range, which approximates closely to that used in our present work, the fraction of the deep water-Čerenkov signal from our detectors arising from muons is close to 0·5 (Armitage *et al* 1973a†), and taking these two features in conjunction, it seems clear that the 10% of signal height level corresponds to about 20% of the muon contribution with a negligible contribution from the soft component. The 50% level will in a similar way correspond to a proportion of all muons which depends in detail upon the time distribution in the two components, but which for Baxter's calculations corresponds in this distance range to the arrival of about 80% of all muons. This is a fraction which can hardly vary very much from one model to another. It is thus reasonable to think of $t_{1/2}$ as physically corresponding approximately to the 20–80% arrival spread of shower muons. Interpretation of the data of Armitage *et al* (1973b, table 3 therein) shows that, in the distance range 400–500 m, the 20–80% arrival spread of muons is about 120 ns, to be compared with the measured value of $t_{1/2}$ of about 130 ± 10 ns.

Important calculations on proton-initiated showers have been made by Dixon and Turver (1974), and use will be made of their conclusions in a later section. At this point we draw attention to their determination of the median muon delay (from a plane shower front) in a 10^{17} eV shower 500 m from the axis as 82 ns, to be compared with the measurements by Armitage *et al* in the 400–500 m distance range of 80 ns. Too much must not be read into this agreement. The energy threshold of the measurements is lower, but the distance from the axis is also significantly smaller.

† The energy threshold (0·3 GeV) here is close to that of the main Čerenkov tanks if the latter are to yield a full muon signal. The threshold for the work of Dixon and Turver is 1 GeV.

The above details are quoted here only to illustrate the general conformity of existing data and the way in which it extends to include the $t_{1/2}$ measurements. They also indicate the extent to which this parameter ($t_{1/2}$) comes from a signal depending heavily on the muon element of the shower front, upon which much of the 'sampling fluctuation' must depend.

3.2. *Average shower-to-shower differences of $t_{1/2}$*

The standard deviation of $t_{1/2}$ measured in the present experiment which is to be attributed to fluctuations of shower development is estimated from the analysis of variance as:

$$\sigma_{\mathrm{f}} = \left(\frac{\sigma_1^2 \nu_1 + \sigma_2^2 \nu_2}{\nu_1 + \nu_2} - \sigma_2^2\right)^{1/2},$$

and, as shown in table 3, has values of the order 5–10 ns. It will be important to develop much more accurate values for this quantity, but it is worth noting that it is not unreasonable that this should increase with primary energy and with distance from the shower axis as is suggested by the difference between group B and group A data.

It is extremely difficult to envisage any sort of defect in measurement or of analysis which would simulate a significant value of σ_{f} were the real value very much smaller. All obvious limitations, and the sampling function of the detectors is probably the most severe, act to diminish and obscure σ_{f}. The only factor which might act otherwise seems to lie in the possibility of observer bias, tending to provoke similar readings within as opposed to between showers. We do not believe that such a bias has been introduced, partly because speculation about such relationships between pulses was something consciously resisted, but in a more generally convincing way because the high degree of measurement agreement between the two observers, and the negligible systematic difference between their average measurements (§ 2.2) are features which are not to be expected in the presence of significant bias. Finally, even were such a bias present in a way to modify σ_{f} (above), it is unquestionably not a feature of the consideration of extreme variations which are the subject of the next section (§ 3.3), nor of the correlation with a second shower development-sensitive parameter indicated in § 4.

If then, σ_{f}, has indeed values of the order indicated, we have to consider whether this might be of trivial origin, in for example, variations of the atmosphere. The strongest variation would then arise from pressure changes, although this is estimated to be less than 10% of what is observed. We have examined for correlation of the 75 group B showers with pressure and have found none, to the present accuracy of work. We therefore remain of the opinion that defects of measurement and treatment of data must be expected to reduce σ_{f} rather than to increase it, if there is any effect at all.

3.3. *Extreme shower-to-shower difference in $t_{1/2}$*

The quantity σ_{f} discussed in § 3.2 has not yet been measured with any great precision, nor has the analysis of shower simulations yet developed to the stage when the measurements can be interpreted in any detail. Nevertheless, what indications there are to be found in, for example, the work of Dixon and Turver (1974) lead to the view that the measured σ_{f} is almost certainly larger than is consistent with an exclusively heavy composition of the primary particles in the energy range ($\sim 10^{18}$ eV) in particular applicable to the group B data. In the present state of predictions about showers, the most significant evidence of the present work must be seen in a single event, which yields the extreme departure from average behaviour in the 75 showers of group B.

This extreme shower (reference number 8902705) would, since the distribution of values of $\overline{\Delta t}_{1/2}$ shown in figure 2 is certainly asymmetric, in any case require comment, but fortuitously it carries greater than normal weight because it also yields measurements of unusually high quality and, moreover, the most serious uncertainty of measurement, that of radial distance, is in this instance negligible. The three individual $t_{1/2}$ values for this shower and their mean, are inserted in figure 2.

The relevant data on this shower are given in table 4 and in figure 3. Density measurements at the inner (150 m) array detectors establish the axis point to within about 5 m, while the distances from the axis to the three 34 m^2 detectors at which the signals are measured are rather less than 500 m because of the inclination of the detector plane by 27° to the shower axis. If the measurements of $t_{1/2}$ are subject to the same uncertainty, $\sigma_{ms}^2 = (\sigma_m^2+\sigma_s^2)^{1/2} \sim 14$ ns, as are the main body of records with $\Delta > 0{\cdot}8$ m^{-2}, then the average of pulses for this shower is 'slow' by (37 ± 8) ns. However, since these are

Table 4. Details of event 8902705 (see also figure 3).

Zenith angle = 27°, azimuth angle = 86°

Detector	Density (m^{-2})	Core Distance (m)	$t_{1/2}$ (ns)
A1	$>10^3$	13	not measured
A2	2·88	475	165
A3	2·65	499	165
A4	3·51	458	170
32	120 (recorded digitally)	133	—
33	84·5 (recorded digitally)	156	—
34	101 (recorded digitally)	142	—
H	0·09	1064	not measured

$\rho(600) = 1{\cdot}6$ m^{-2}, $E_p \sim 1{\cdot}4 \times 10^{18}$ eV

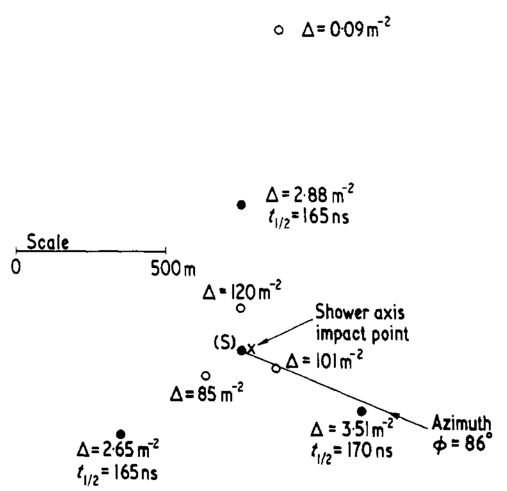

Figure 3. Measurement details of shower 8902705 plotted in the plane of the shower front.

particularly favourable pulses and with $\Delta \sim 3\ m^{-2}$ this uncertainty may well be overestimated. If we take the crude uncertainty represented by the differences of the three measurements of this particular event from their own average, we would derive (37 ± 6) ns. Accordingly it is extremely unlikely that $t_{1/2}$ for this shower is slow, on the average of the three detectors, by as little as 20 ns and it is probable that it is slow by 30 ns or more. Figure 3, in which the detectors are shown projected onto the shower plane, illustrates the basic data of this shower, and in particular the very small range of uncertainty, and the internally-cancelling nature in the uncertainty, of the three values of r.

Data from simulations for the interpretation of this measurement are scanty and not directly relevant, but we draw attention to the results given by Dixon and Turver (1974). For 10^{17} eV incident protons, and not taking account of any possible increase in the interaction cross section, they predict that 5% of incident protons will yield a median muon delay at 500 m retarded by 38 ns compared with the average value, while in a diagram they show very strikingly the magnitude of the difference of shower development through the atmosphere necessary to produce this feature in 5% of protons with the altogether smaller variations to be expected from fragmentation of heavy nuclei. While recognizing the limitations of comparing a retardation of the median muon with the measured value of $t_{1/2}$, we regard this particular shower as extremely strong evidence for the existence of light (proton or conceivably α) primaries at an energy of about 10^{18} eV.

The small number of observations of high quality (group B) yet available, the gaps in simulation material and uncertainty about the proton cross section make any estimate of the proportion of light primaries premature at this stage.

4. Comparison of the behaviour of $t_{1/2}$ with that of other development-sensitive parameters

It has now been recognized for some years (Wilson 1970, 1972, Dixon and Turver 1974) that a really effective study of primary composition is likely to require the combination of measurements of more than one sensitive parameter. Recent simulations (Marsden *et al* 1971, Dixon and Turver 1974) have confirmed that the ratio of Čerenkov signals in the normal Haverah Park detectors of the form $\rho(r)/\rho(600)$, to which attention was first directed by Dr R J O Reid, is indeed such a sensitive parameter when r is of the order of 50 m, and an important development of the Haverah Park array is now in progress to allow accurate measurement of r at distances like 50 m from the shower core, so that reliable measurements of this ratio can be made for distances of this order.

While distances of about 50 m are the basis of the ongoing development of equipment, the quoted ratio is predicted to exhibit sensitivity to shower development, although less pronounced, at distances of about 100 m.

We are indebted to Mr D M Edge for providing us with the best possible estimates of $\rho(100)/\rho(600)$ from existing shower data of 24 of the showers for which we have measurements. These are showers in which the axes fell close to the central detector and the measurements described in earlier sections were made at two or three of the outer detectors of the main array (figure 3 is an example of one such shower). The array available during the collection of our data was, of course, in no way adapted for the optimum determination of $\rho(100)/\rho(600)$, and the values provided for us fall far short in quality from what will shortly be available: they are also of very different quality among themselves, and refer to showers in our sample which also range from some of the most reliable measurements to group A data of much lower quality. We have made no attempt to weight the various showers, and the very mixed quality of the data only further emphasizes the significance of the results obtained when the two parameters are used in combination.

The data for the 24 showers are illustrated in figure 4, while an analysis of variance of the form set out in table 3 but restricted to these showers with and without the $\rho(100)/\rho(600)$ ratio is given in table 5. The data available for the shower illustrated in figure 3 are particularly good for both parameters; this shower is identified in figure 4.

Both modes of presentation show strikingly that even with this limited amount of data, one element of which is still, at best, in a very primitive state, the combination of

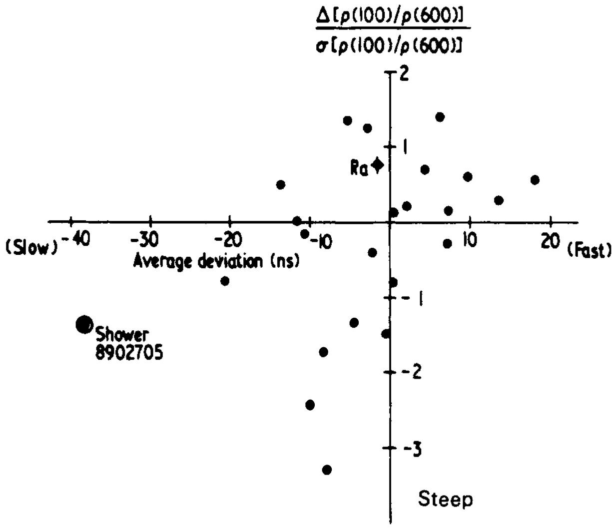

Figure 4. 24 showers of the $t_{1/2}$ analysis for which a determination of the near-axis structure function was possible. The scale of $t_{1/2}$ shows deviations from the average in nanoseconds; the structure-function scale is in standard deviations from the ratio extrapolated from numerous measurements around 500–600 m. Shower 8902705 is indicated. 'Ra' is a shower referred to in the text for which a radio signal has also been measured.

Table 5. Analysis of variance: inclusion of $\rho(100)/\rho(600)$ measured ratio.

24 showers	(*a*) $t_{1/2}$ data only	(*b*) $t_{1/2}$ data + ρ-ratio data
Between-shower variance σ_1^2	2·22	2·70
Number of degrees of freedom	23	23
Within-shower variance σ_2^2	0·99	0·97
Number of degrees of freedom	42	66
$F = \sigma_1^2/\sigma_2^2$	2·26 $1\% < p < 2{\cdot}5\%$	2·79 $p \sim 0{\cdot}1\%$
$\dfrac{\sigma_1 - \sigma_2}{\text{Standard error of difference}}$	2·29	3·23

parameters strengthens still further, and probably conclusively, the view that quantitative features of shower-development parameters can be derived. The data of table 5 are perhaps the most clear cut. Using only 24 rise-time showers the probability that the measured variance might arise by chance is of the order of 2 %. The addition of the quite primitive ρ-ratio data already reduces this probability to no more than 0·1 %.

We are indebted to Dr H R Allan and Dr J K Jones for information about the only shower in this group for which a radio signal has been measured. This shower (figure 4) is 'average' as to $t_{1/2}$ and the ρ ratio. Its radio signal is also 'average'!

5. Summary and conclusions

The evidence is that features of shower fronts which relate to fluctuations of shower development can be detected at distances of about 500 m from the shower axis in events up to at least 40° from the zenith. These features are observable in a relatively small group of showers (< 100) for each of which a total of about 100 m^2 of detector lies in three widely-separated parts of the shower. Although detailed material from the interpretation of these measurements in terms of simulation data does not yet exist, there is sufficient information to suggest strongly that some primary particles at energy 10^{18} eV are light, probably protons but possible α particles.

A very preliminary combination of shower front measurements with estimates of lateral distribution function variations of showers at about 100 m from the axis shows that these features are correlated, and emphasizes the importance of the use of such parameters in combination.

It is important to observe that what now seems capable of observation are the extreme fluctuations of shower development derived from proton primaries: while this feature, when better understood, ought to yield a determination of the proportion of protons, perhaps of α particles, it is only for a very few individual showers that any statement as to the nature of the particular primary is foreseeably possible.

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