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The arrival time distribution of muons in extensive air showers

M L Armitage, P R Blake and W F Nash

Department of Physics, University of Nottingham, University Park, Nottingham NG7 2RD, UK

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Abstract. The time spread of muons within EAS has been determined by measuring the time of arrival of individual muons with respect to the extreme shower front with an accuracy of ± 10 ns. The integral time distributions averaged over a group of showers are presented as a function of shower parameters. For near vertical showers it is found that the 10%–90% time spread of muons increases from about 100 ns at an EAS core distance of 150 m to about 160 ns at 450 m. These results are shown to be in reasonable agreement with predictions based on model calculations.

1. Introduction

A measurable parameter of large EAS (primary energies $\gtrsim 10^{17}$ eV) is the time spread in arrival of the secondary particles at a ground level detector situated at a known distance from the EAS core. The sensitivity of the results of such measurements to yielding details of the longitudinal development of the EAS has been considered in some recent EAS model calculations, in particular those of Dixon and Turver (1974). These authors have shown that time spread measurements of the particles detected at sea level can give an indication of the height of the first interaction of the particle initiating the EAS and therefore an indication of the mass of the primary cosmic ray particle.

In individual showers, if enough particles are incident on the timing detector, the measurement of the 10% to 90% amplitude response time spread (or similar parameter) is a sensitive indicator of longitudinal development. These measurements can be directly compared with corresponding predictions derived from the model calculations assuming particular heights of EAS initiation. Such study requires the presence of a complex air shower detector array to establish the location of the EAS core with good accuracy. In addition, in order to obtain a high enough density response, the measurements must be made on large EAS at fairly close core distances with large area detectors.

Currently, timing measurements using the 34 m^2 water Čerenkov detectors at Haverah Park seem to be most promising. Initial analysis based on the normal pulse height records from the array has been published (Watson and Wilson 1974). The authors are able to conclude that their data strongly suggest protons or α particles to be amongst primaries at energies of the order of 10^{18} eV. Such primary mass discrimination is the major current aim of the Haverah Park array. An improved recording system, specifically designed to measure rise times in the Čerenkov tank response has now been developed (Lapikens 1974) and is in operation. This promises to yield more refined data than hitherto available.

In correlating the experimental data with the model predictions difficulties arise in separating the contribution of the electromagnetic component from that of the muon component. Measurements on the mean time spread of muons alone have previously been carried out at Haverah Park using shielded scintillators (Blake and Harris 1970). These results established the presence of a proportion of muons arriving more than 100 ns behind the shower front. This paper describes more recent measurements made with the same shielded scintillators but with a recording system designed to determine the arrival time of each detected muon with considerably improved resolution. The time of arrival of each muon was measured with respect to the 'first detectable signal' from the neighbouring 34 m^2 water Čerenkov detector to an accuracy of ± 10 ns.

2. Experimental details

2.1. Apparatus

The muon detector was situated at the central station of the Haverah Park EAS array. The 10 m^2 of liquid scintillator, shielded by 20 cm of Pb, were divided into eight separate units. The outputs from the scintillator units were recorded separately by delaying, mixing and displaying the eight channels on the two beams of a double beam oscilloscope. Also gated onto each timebase, suitably delayed, was a highly amplified response signal from the neighbouring 34 m^2 water Čerenkov tank detector. The start of the Čerenkov signal served as a reference point from which to measure the time position of the muon pulses. The oscilloscope's timebases (1 $\mu s\ cm^{-1}$) were triggered by the Haverah Park EAS array and a film record of each event was obtained. The records were then correlated with the main EAS analysis.

2.2. Calibration

The scintillator pulse height responses were calibrated by independently selecting single vertical muons and deriving the mean detector response to such particles.

The timing calibration was achieved by triggering the recording system off 'local EAS' in which any time spread is expected to be small (<10 ns). Local EAS' were small EAS causing measurable pulse heights in several neighbouring detectors. This technique not only enabled the 'zero' time position of the pulses from each unit to be determined but also served as a means of establishing the measuring resolution of the method.

2.3. Analysis of film records

The technique depends on the fact that in the majority of EAS triggering the Haverah Park array only one muon passed through any one shielded detector unit (1·25 m^2). In the analysis of the film records only pulse responses which were regarded as arising from a single muon were considered for measurement. In practice the criterion used was to measure all pulses whose amplitude corresponded to less than $\frac{3}{2}$ times the mean for a single particle.

The great advantage of this technique is that all selected pulses, although differing somewhat in amplitude, have closely similar shapes. The 10% to 90% rise time of an individual muon pulse was close to 100 ns. This arose from a combination of the photomultiplier tube, head amplifier and delay lines. In particular the immediate breakaway of the pulse from the timebase was slow and therefore the exact position of the breakaway was impossible to measure with high resolution. However, by fitting a fixed function of variable amplitude to the fastest rising middle region of the pulse the position of the pulse on the timebase could be determined to a high degree of accuracy estimated to be about 1 ns.

The reference point on the timebase chosen from which to measure the position of the muon pulses was set by gating into the beginning of the two timebases the first response detected from the EAS by the 34 m^2 water Čerenkov detector situated next to the muon detector. Although using the minimum possible delay line (4 μs of high quality coaxial cable) the uncertainty in determining the breakaway point of this pulse from the timebase contributed most to limit the timing resolution of this technique. The method of fitting a function was not possible in this case due to the complex nature and fluctuations of the total Čerenkov tank response.

Tests of this analysis technique using the 'local shower events' produced histograms with standard deviations close to 10 ns. This can be regarded as a measure of the timing resolution of the method.

3. Details of results

During a period of about twelve months running, data on 4715 muons were analysed. The EAS included in the analysis were initiated by primary particles of energy about 10^{17} eV or more and satisfied the conditions that the shower axes were located inside the 500 m array perimeter and that the 150 m array was also in operation. These conditions enabled the core locations to be established with an accuracy of approximately 20 m or less. Table 1 indicates how the EAS were distributed with respect to zenith angle and core distance.

Table 1. Number of muons included in analysis binned according to EAS core distance and zenith angle.

	Number of muons			
R (m)	$100 \leqslant R < 200$	$200 \leqslant R < 300$	$300 \leqslant R < 400$	$400 \leqslant R < 500$
Zenith angle				
$\theta < 25°$	520	497	369	299
$25° \leqslant \theta < 35°$	477	397	267	196
$35° \leqslant \theta < 45°$	329	287	232	157
$45° \leqslant \theta < 55°$	283	154	142	109

In each bin the measurements on all the muons were combined to give the overall average time spread distributions of muons in EAS. The integral distributions for the four core distance ranges with zenith angles less than 25° are shown in figures 1 to 4. The errors indicated on each point are calculated statistical errors.

In order to quantify the distributions the time intervals between 10% and 90% of the distributions were measured (referred to as T) and are indicated on the four diagrams. The errors quoted represent the limits placed on T by the statistical uncertainty.

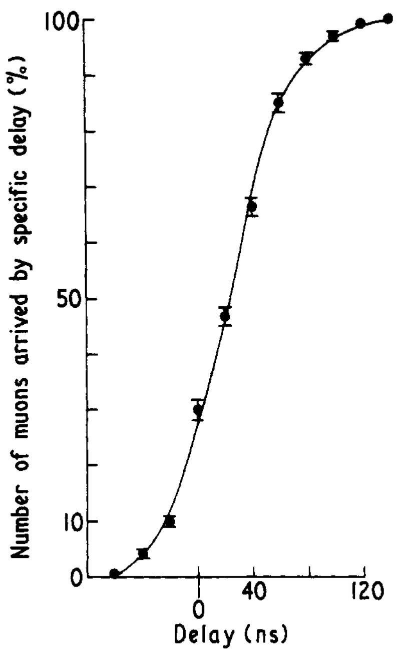

Figure 1. Integral time delay distribution of muons for $100 \leqslant R < 200$ m. $\theta < 25°$, $T = 96(\pm 8)$ns.

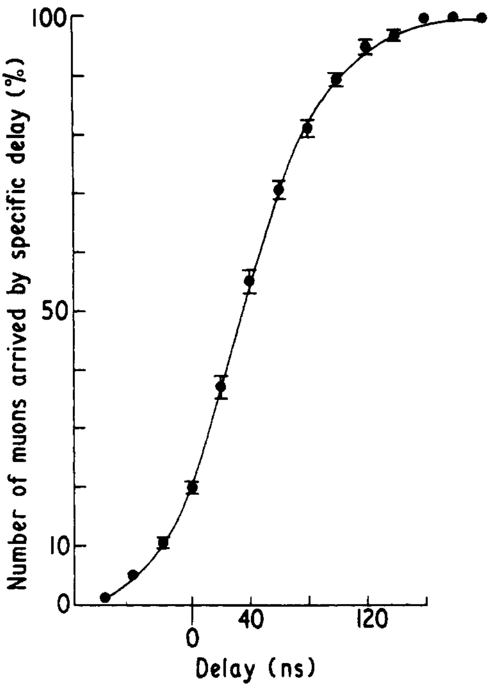

Figure 2. Integral time delay distribution of muons for $200 \leqslant R < 300$ m. $\theta < 25°$, $T = 126(\pm 10)$ns.

It is apparent from the plots that the value of T increases with core distance from about 100 ns at 150 m to about 160 ns at 450 m from the core. No detectable change in these distributions was observed as a function of shower size over the primary energy range 10^{17}–10^{18} eV. Similar distributions were drawn for zenith angles greater than 25°. Table 2 shows the value of T obtained for each of the core distance bins in the different zenith angle intervals.

It is apparent from these results that the distributions are not a strong function of zenith angle.

4. Discussion of distributions

The presence in the distributions of muons arriving ahead of the zero calibration point must be attributed to a combination of the measuring resolution of the technique and the effect of the reference point not always reflecting the extreme shower front. The latter effect arises from the possibility that the foremost particles in the shower front miss the 34 m^2 Čerenkov detector but get recorded by at least one of the muon units. This possibility is minimized by the large area of the Čerenkov tanks, by the amplification of its response so that the first particle to arrive is clearly observable, and by the fact that normally the Čerenkov detector has a response at least equivalent to 20 vertical muons of which, at the core distances under analysis, about one-third are actual muons.

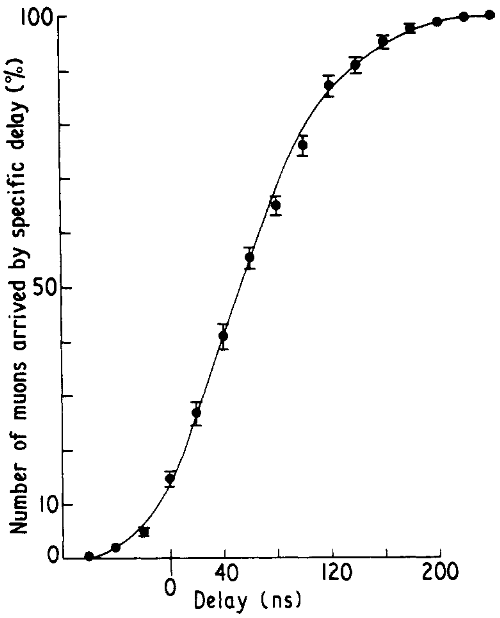

Figure 3. Integral time delay distribution of muons for 300 ⩽ R < 400 m. θ < 25°, T = 144(±12)ns.

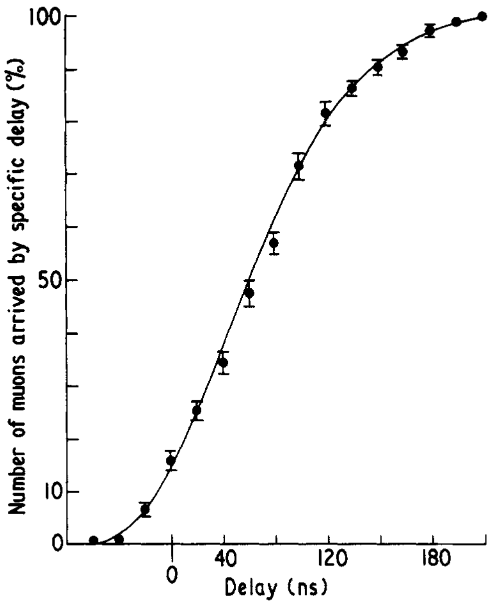

Figure 4. Integral time delay distribution of muons for 400 ⩽ R < 500 m. θ < 25°, T = 164(±16)ns.

Table 2. Values of T (10%–90%) as function of core distance and zenith angle.

	Time T (10%–90%) (ns)			
Core distance (m)	100 ⩽ R < 200	200 ⩽ R < 300	300 ⩽ R < 400	400 ⩽ R < 500
Zenith angle				
θ < 25°	96 (±8)	126 (±10)	144 (±12)	164 (±12)
25° ⩽ θ < 35°	102 (±8)	134 (±8)	142 (±12)	156 (±14)
35° ⩽ θ < 45°	106 (±8)	117 (±14)	143 (±12)	154 (±16)
45° ⩽ θ < 55°	102 (±12)	132 (±14)	140 (±14)	140 (±18)

The experimental distributions themselves strongly indicate that it is the resolution effect which largely controls the 'early' tail. The shape of the tail remains substantially constant with core distance. If the 'sampling' was a major contributing factor the 'early' tail could be expected to grow with increasing core distance as the probability of the first detected particle being behind the extreme shower front becomes larger.

This 'sampling' can also be expected to affect the shape of the derived distribution. An attempt was made to calculate the effect of 'sampling'. Choosing a shower size close to the threshold for the array, a Monte Carlo calculation was undertaken to find the probability distribution in time for the first detected response from the Čerenkov tanks relative to the extreme shower front. It was assumed that the leading particles in the front were muons (Trumper *et al* 1971). Such a calculation was carried out for various core distances. Table 3 lists the derived mean time delays between the extreme shower front and the first detected particle in the Čerenkov tanks as suggested by these calculations. The calculations were performed using the predicted arrival time distribution for muons of Dixon and Turver (1974).

It is seen that although the effects are small they cannot be neglected at the larger core distances. To a first approximation the Δt of table 3 can be taken as an addition correction factor to the values of T quoted in table 2.

Table 3. 'Sampling' effects on the time distributions.

Core distance (m)	Δt(ns)
150	2·5
250	4·6
350	6·8
450	16·0

5. Physical causes of the muon time spreads

The causes of the muon time spreads in EAS can be considered under two headings: path length effects and velocity effects. The length of the path travelled by a muon (and its parent particles) before striking a detector at a particular distance from the core of the shower is dependent on the height of production of the muon as well as scattering (both geomagnetic and Coulomb) in the atmosphere. EAS model calculations show that scattering contributions are almost negligible, even for the muons close to the threshold detection energy of 0·3 GeV. The dominant effect in determining the path length of the muon before striking the detector is its height of production (geometric delay). Figure 5 shows the calculated time delays for muons due to geometric delays.

In addition one must consider velocity delays arising from muons having the same production height but different energies. The delays expected as a function of height and energy (Baxter 1967) are shown in figure 6.

As the median energy of muons in EAS over the core distance range 200 to 500 m is about 3 GeV at detection, the geometric time spread can be expected to dominate the observations. Again this conclusion is supported by the observed distributions. The measured delay behind the shower front varies strongly with core distance in the manner suggested by the geometric effect. The velocity variation with core distance would be much less marked.

6. Comparison of the time distributions with model predictions

Marsden (1971) has calculated the muon arrival time distributions for an EAS of primary energy 10^{17} eV at a core distance of 400 m and zenith angle of 25°. The interaction model used was the Hillas model A. This model differs slightly from the more preferred model

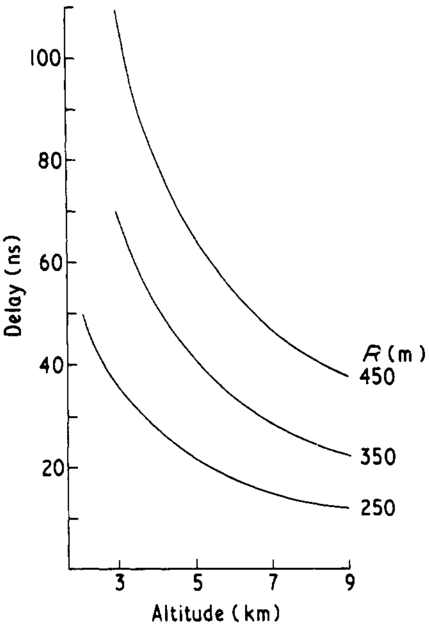

Figure 5. Calculated time delays of muons due to geometric delays.

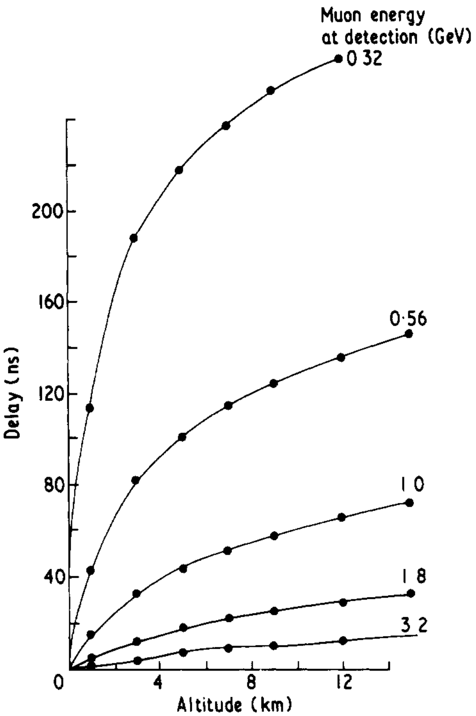

Figure 6. Calculated time delays of muons due to velocity delays.

E'which fits better the muon density measurements at Haverah Park (Armitage *et al* 1974).

The time spread distribution was calculated considering geometrical delays only and produced a 10%–90% spread of 130 ns. This compares with the experimental interpolated value from table 2 of 154 ($\pm$12) ns. The comparison can be regarded as encouraging particularly as the non-geometric additions to the delays have been ignored in the calculations.

The more recent detailed models of Dixon and Turver (1974) have also led to predictions of the muon time spread. Some details of the predicted distributions have been published (Dixon 1974). These predicted distributions show close agreement with the experimental results presented in figures 1 to 4. For example, the calculations predict a median muon delay of about 80 ns for a core distance of 450 m—close to that observed (figure 4).

7. Heights of origin of muons in EAS

If one makes the assumption that all the measured delays are due to path difference effects then it is possible to calculate the median height of production of the muons. Table 4 shows the median values of the differential time spread distribution for EAS of zenith angles less than 25°. The indicated 'sampling' corrections are added in before calculating the production heights.

Table 4. Median production heights calculated assuming delays are geometric only.

Mean core distance (m)	Median time delay (ns)	Sampling correction (ns)	Production height (km)
150	43·7	2·5	0·8
250	53·4	+ 4·6	1·8
350	71·2	+ 6·8	2·7
450	83·5	+ 16·0	3·4

The median production heights are calculated assuming that particles in the extreme shower front originate more than about 15 km above sea level. The results indicate that the median production height increases with core distance. This is as predicted by model calculations. The height of production figures given in table 4 agree well with the model predictions at the larger core distances, but are too low in the region around 200 m from the core. The models here predict median production heights of about 2·5 km. It is reasonable to assume that contributions from non-geometric delays become important in this region. Indeed, assuming that only half the measured delay at 150 m is due to geometric effects a production height of 1·9 km is indicated, which is much closer to the models. The mean delay due to velocity differences would be expected to increase slowly with core distance as the average muon energy decreases. However, the geometric delays increase at a much faster rate and dominate at around 300 m or more.

8. General conclusions

The measurement of muon time spread in EAS using the technique described in this paper has yielded results which are consistent with model calculations. This method of analysis is however only suitable for a limited density range (~ 1 particle m^{-2}) and hence cannot be usefully extrapolated to the high particle numbers required in order to investigate fluctuations between showers.

The area of the muon detectors at Haverah Park has now been extended to $32\ m^2$ and the timing measurements are being improved, including faster photomultipliers and electronics and using further recording techniques. It is hoped by this means to investigate the longitudinal development of individual showers. This we hope will lead to some more definite conclusions regarding the mass composition of the primary particles.

Acknowledgments

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