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1972 J. Phys. A: Gen. Phys. 5 125

(http://iopscience.iop.org/0022-3689/5/1/017)

J. Phys. A: Gen. Phys., Vol. 5, January 1972. Printed in Great Britain

Muon bundles in large EAS

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MS received 1 June 1971

Abstract. The Nottingham muon detector at Haverah Park has shown up events which contained an unexpected close grouping of muons at large distances from the cores of extensive air showers (EAS). This paper is concerned with the detailed analysis of these events. The results are considered in relation to similar groupings observed near the core of showers by the Moscow State University group.

1. Introduction

The installation of a muon detector having a high spatial resolution at the central station of the Haverah Park air shower array (Blake *et al* 1971) has enabled a study to be made of the spatial grouping of muons in EAS from primary particles in the energy range 10^{17}–10^{19} eV. Routine analysis of film records has shown up events in which unexpected close grouping of muons appears to have been present. A detailed analysis of all the film records was undertaken with a view to positively identifying the presence of such 'muon bundles'. This paper reports the results of that analysis.

2. Description of apparatus

The detector ($12\ \mathrm{m}^2$) was made up of three separate units of equal area. Two of these units were of identical design and consisted of a multilayer sandwich of neon flash tubes and lead absorber (figure 1). The flash tubes (2 m × 1·8 cm) were arranged in four double layers each separated by 5 cm of lead and 2·5 cm of supporting steel. A determination of both the number of muons (> 300 MeV) and electrons striking the detector could thus be carried out. The third unit (figure 2) had a similar construction to the other units with the addition of two vertically separated trays of accurately located flash tubes placed on top. Each of these trays consisted of ten layers of flash tubes, five in each of two perpendicular directions. The bottom tray had a further 5 cm thickness of lead

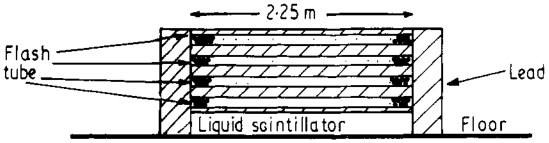

Figure 1. Schematic drawing to scale of identical detecting units 2 and 3.

absorber above it. This combination enabled the muon tracks to be observed in two perpendicular planes.

The liquid scintillator at the base of all three detector units was included for fast timing measurements of the muons but has no relevance to the present analysis.

The flash tube units and recording cameras were triggered by the main Haverah Park array which detected EAS produced by primaries of 10^{17} eV and above, falling on the array of water Cerenkov detectors at the average rate of forty events a day. The Cerenkov detector responses yielded the size of the shower, its core location and zenith and azimuthal angles within the accuracies quoted by Tennent (1968).

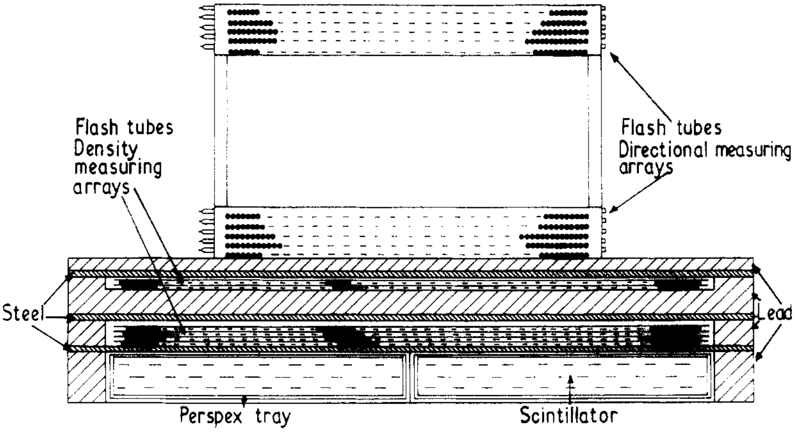

Figure 2. Schematic drawing to scale of detecting unit 1 including the trays of crossed flash tubes.

3. Search for muon bundles

Some 6000 showers were included in the analysis of varying primary energy ($10^{17} \rightarrow 10^{19}$ eV) core distance (100 → 1000 m) and zenith angle (0° → 80°). Three distinct methods of analysis were used: (i) the distribution of distances between muons in one plane; (ii) correlation of the distribution of distances between pairs of muons in two planes; (iii) a search for individual muon bundle events in both planes.

3.1. Study of the distances between muons in one plane

The object of this study was to compare the experimental distribution of spacing between muons observed in one plane with that expected for a spatially random flux of EAS muons. Analysis was carried out on film records in which between 4 and 10 muons inclusive fell on a detector unit, representing muon densities of $1\ \mathrm{m}^{-2}$ to $2\cdot5\ \mathrm{m}^{-2}$ and arising from a mean shower core distance of 240 m. This range of densities was chosen after consideration of computer calculations simulating different numbers of muons falling randomly on the detector. For each selected number of muons, over the range 2 to 15 muons per detector unit, a Monte Carlo calculation on 30 000 muons was carried out. This calculation assumed that the muons striking the detector were randomly spaced with respect to each other and also incorporated the spatial resolution of the detector together with its edge effects.

If the spacing in one plane between neighbouring muons is expressed in units of mean spacing for that particular density then the calculated distributions of expected spacings for densities in the range 4 to 10 muons per detector are nearly identical and can be represented by a common curve.

Two zenith angle ranges were considered, namely near vertical showers with $\theta \leqslant 30°$ and more inclined showers with $\theta \geqslant 40°$. As the analysis here was carried out in one plane the range of azimuthal angles for the high zenith angle showers was also restricted so that the muons appeared nearly vertical in the observed plane, thus maintaining the same baseline length of the detector independent of the actual zenith angle of the shower.

The distance spacing between neighbouring muons was measured and expressed in units of mean spacing for that number of detected muons. Figure 3 shows the experimental points thus obtained for showers with $\theta \leqslant 30°$. The histogram in figure 3 is the calculated distribution assuming the muons fall randomly over the area of the detector. A χ^2 test shows that the experimental histogram is consistent with the random distribution curve within a 75 % confidence limit. Similar good agreement was obtained for the inclined showers ($\theta \geqslant 40°$).

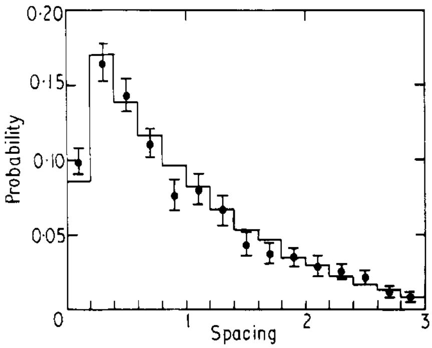

Figure 3. Comparison of experimental histogram of spacing between neighbouring muons with that expected from a random flux. Plot of single spaces; $\theta < 30°$, 4–10 particles per event.

This analysis is made more sensitive to muon beams of greater than two particles if a plot is made of the distance spread of muons taken in groups of three. Such a plot is shown in figure 4 for showers with $\theta \leqslant 30°$ and again a χ^2 test shows it to have a 85 % confidence limit of being in agreement with that expected from randomly spaced muons.

3.2. Pairs of muons in perpendicular planes

In order to determine whether pairs of muons appearing close together in one plane exhibit a random distribution of spacings in the other perpendicular plane, events ($\theta \leqslant 30°$) were chosen in which two muons only passed through the crossed tray detector (figure 2). These represent densities of approximately 0·6 m^{-2} and arise from a mean shower core distance of 390 m. The distances between muon tracks were measured in two planes and then correlated. The results are set out in table 1, showing the mean distance separation X measured in one plane for a selected narrow interval distance separation in the other plane ΔY. It was found by a least squares technique that there was no correlation between X and ΔY or between Y and ΔX. This is consistent with a random flux.

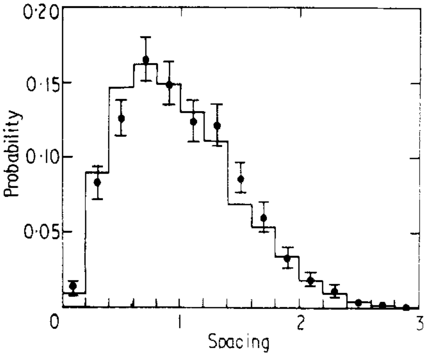

Figure 4. Comparison of experimental histogram of spacing of muons taken in groups of three with that expected from a random flux. Plot of double spaces: $\theta < 30°$, 4–10 particles per event.

Table 1. Mean spacing in X plane for each ΔY interval, and mean in Y plane for each ΔX interval

ΔY and ΔX	Mean X for ΔY	Mean Y for ΔX
1	$0{\cdot}40 \pm 0{\cdot}04$	$0{\cdot}37 \pm 0{\cdot}04$
2	$0{\cdot}39 \pm 0{\cdot}04$	$0{\cdot}37 \pm 0{\cdot}04$
3	$0{\cdot}34 \pm 0{\cdot}04$	$0{\cdot}32 \pm 0{\cdot}04$
4	$0{\cdot}38 \pm 0{\cdot}04$	$0{\cdot}35 \pm 0{\cdot}04$
5	$0{\cdot}33 \pm 0{\cdot}04$	$0{\cdot}31 \pm 0{\cdot}04$
6	$0{\cdot}34 \pm 0{\cdot}04$	$0{\cdot}33 \pm 0{\cdot}04$
7	$0{\cdot}32 \pm 0{\cdot}04$	$0{\cdot}31 \pm 0{\cdot}04$
8	$0{\cdot}31 \pm 0{\cdot}04$	$0{\cdot}34 \pm 0{\cdot}07$
9	$0{\cdot}31 \pm 0{\cdot}04$	$0{\cdot}32 \pm 0{\cdot}10$
10	$0{\cdot}37 \pm 0{\cdot}04$	$0{\cdot}24 \pm 0{\cdot}10$

3.3. *Individual 'muon bundles'*

The film records show a number of events in which there appears to be close grouping of particles observed in both planes. The particular characteristics of such an event were as follows:

(i) zenith angle = 57°, shower core distance = 200 m, total charged particle density from neighbouring Cerenkov tanks ($34\ \mathrm{m}^2$) = $1{\cdot}24\ \mathrm{m}^{-2}$.
(ii) Muon density from other two stacks ($8 \cos 57°\ \mathrm{m}^2$) = $1{\cdot}20\ \mathrm{m}^{-2}$.
(iii) Expected numbers of muons on counting trays ($4 \cos 57°\ \mathrm{m}^2$) = 2·5, actual number of muons on counting trays = 9.
(iv) In one plane, 5 muons within 20 flash tubes spacing. In other plane, 5 muons within 40 flash tubes spacing.
(v) Evidence (from detailed study of the photograph) that 4 of the muons in each bundle are the same muons. There exist other event records of similar character.

Any statistical assessment of these events is somewhat subjective because of the unique nature of each event. Of 6000 showers scanned about 800 records were of the type that would have shown up 'muon bundles' if they had been present within the detector unit. In order to make an objective classification, an event record of three or more muons was considered as a muon group if all the muon tracks were confined to within a quarter of the detector width in both planes. Using this criterion 18 detector records show evidence for muon grouping. The probability that these are all attributable to random fluctuations is less than 5%. This result does not contradict the analysis of § 3.1 which is not sensitive enough to show up the small number of events involved.

The angular spread of the muons in the detector for the 'muon bundle' events has been compared with those obtained for 'normal events' (2·5°). It appears that the muon tracks in the bundle type events are less spread (< 2·0°) than those seen in normal events. However angular spread depends on many parameters such as zenith and azimuth angles and core location. It is therefore premature to draw any firm conclusion on this feature from the 18 events examined so far. A close study of the angular spread will be most important when more events are available for analysis.

4. Discussion

The good agreement between the theoretical and experimental curves of figures 3 and 4, together with data shown in table 1 suggest that in general muons arrive at the detector randomly spread within the dimensions of the detector. However, there exist a few event records in which the muons do not appear to be spread randomly.

Some ten years ago the Moscow State University workers reported experimental evidence for the existence of narrow beams of high energy muons in the core region of EAS (Vernov *et al* 1962). At that time it was suggested that these could arise from nuclear interactions having exceptionally high multiplicities coupled with extremely low mean transverse momenta; or, alternatively, they could be explained as the result of the decay of very short-lived parents. More recent observations of muon groups by the Moscow workers using wide-gap spark chambers were reported at the Budapest cosmic ray conference in 1969 (Vernov *et al* 1971).

It must be emphasized that the experimental details at Moscow were different from those at Haverah Park in two important respects. Firstly, the detector was situated at a depth of 40 Hg cm^{-2} with a muon energy threshold of approximately 10 GeV compared with about 300 MeV for the ground level Haverah Park experiment. Secondly, the Moscow group were sampling very much closer to the core of the shower than can be achieved with an array investigating the much higher primary energy range of the Haverah Park station (10^{17}–10^{19} eV). The observation of narrow beams of muons within the Haverah Park detector was not therefore expected, as processes such as those suggested by the Moscow group would be expected to be confined to the core region.

The recent experimental technique used by the Moscow workers (Vernov *et al* 1965, 1971) compares the densities of muons on a 4 m^2 spark chamber with those observed simultaneously on a 40 m^2 Geiger–Muller hodoscope placed below the spark chamber. The presence of muon bundles was deduced by comparing experimental histograms with the expected density fluctuations. However, it is not clear from their published work that they have been able in their calculations to adequately take into account the uncertainties in the lateral distribution function of particles near the shower core, the precision of the core location or any biasing effects due to their triggering conditions. Wdowczyk and Wolfendale (1971) have pointed out that Hibner *et al* (1971) obtain a frequency of muon bundles a factor of ten smaller than that claimed by the Moscow group.

In the same paper Wdowczyk and Wolfendale suggest that such 'muon bundles' might arise from the coherent production of pions, this theory being consistent with the lack of observation of 'muon bundles' by the Utah group (Keuffel *et al* 1971). The assumption that the groups of muons detected in the present experiment are the decay products of coherently produced pions from a nuclear active parent near the core of the shower, requires that the opening angle of the decay muons be less than 10^{-4} rad for them to remain collimated within 0·5 m at the detector. Further, if the strong collimation of the muons is to be unaffected by Coulomb scattering the muons must have an energy of 50 GeV. This implies that the particle responsible for the coherent production had an energy of 200 GeV with an associated transverse momentum (p_t) of about 10 GeV/*c*. This is considerably in excess of the mean value of 0·4 GeV/*c* which is normally accepted. The observed frequency of 'muon bundles' would imply that at least 1 % of all detected muons in EAS ($>$200 m from the core) are produced from parents with high transverse momenta.

Bakich *et al* (1970) and Miyake *et al* (1971) have claimed evidence for the existence of high p_t ($\gtrsim$10 GeV/*c*) in studies of the cores of EAS. The percentage of events which could be interpreted as due to high p_t varied with shower size but was in the range 25 %–75 %. However, Matano *et al* (1968) and Samorski *et al* (1971) from their experiments concluded that only 1·3 % of their events could be interpreted as being due to high p_t.

A possible suggestion is that 'muon bundles' are produced locally by muon photonuclear interactions. The photonuclear cross section has been measured directly up to 20 GeV, and there is significant indirect evidence to indicate that it does not increase rapidly with energy. Using the currently accepted value for the photonuclear cross section and assuming that the particles produced are sufficiently near to the detector to remain collimated and not interact, gives an upper limit of 0·02 events due to this process as compared with the 18 observed.

5. Conclusion

It seems to the present authors, from the data so far published, that the existence of 'muon bundles' as a distinct phenomenon has yet to be firmly established. Because of the complex nature of events recorded on the Haverah Park apparatus, it is extremely difficult to make an accurate statistical assessment of the possible 'muon bundle' candidates. However, both the Moscow work and that reported here have yielded sufficient positive results to make further investigations necessary.

Acknowledgments

We wish to acknowledge the continued support of the Science Research Council in financing the experiment and the indispensable help of our colleagues at the Haverah Park research station. We are particularly indebted to A. Morley for his help in constructing the apparatus and D. W. E. Thomas for his help in operating it.

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