Recent measurements of the muon component of large cosmic ray air showers

1974 J. Phys. A: Math. Nucl. Gen. 7 1010

(http://iopscience.iop.org/0301-0015/7/8/008)

J. Phys. A: Math., Nucl. Gen., Vol. 7, No. 8, 1974. Printed in Great Britain. © 1974

Recent measurements of the muon component of large cosmic ray air showers

H E Dixon, A C Machin†, D R Pickersgill‡, G J Smith and K E Turver
Department of Physics, University of Durham, Durham, UK

Received 3 October 1973, in final form 20 December 1973

Abstract. Measurements are reported for the lateral distribution of muons of energy greater than 1 GeV in large air showers. The measurement which was made with the modified Haverah Park spectrograph extends from core distances of 30–600 m and is in satisfactory agreement with the results of computer simulations.

Data on the differential momentum spectra of muons at core distances of 200–600 m in large air showers are reported which are in good agreement with the results of recent computer simulations and do not show the excess of distant energetic muons which featured in earlier measurements.

1. Introduction

During the period 1964–69 comprehensive measurements were made on the muon component of near vertical large extensive air showers (EAS) using the original Haverah Park magnet spectrograph (to be referred to as the mark I spectrograph). The data included details of the distribution in sign of the electric charge, momentum and core distance of the muons in EAS produced by primary particles of about 10^{17} eV, together with information on the angles made by the muons with the shower core direction and the charge ratio of muons in specified regions of the shower front resulting from the deflection of the muons in the geomagnetic field. These data together with possible interpretations have been reported previously (Earnshaw *et al* 1967, 1971, 1973, Orford *et al* 1968, Machin *et al* 1970). Particular interest has arisen in the momentum spectrum of muons at core distances of around 300 m in showers of primary energy 10^{17} eV in the region of momentum 50–100 GeV/c which was near the limit of resolution of the mark I spectrograph. These measurements indicated the presence in large showers of a greater number of energetic distant muons than expected on the basis of the then available shower simulations.

During 1970 the magnet spectrograph was modified to have a higher momentum resolution. Additional air shower detectors were also incorporated into the Haverah Park array resulting in more reliable measurements of the distance of the spectrograph from the shower core.

This paper reports the data from two and a half years of operation of the modified spectrograph (to be referred to as the mark II spectrograph). The measurement of prime concern has been the determination of the density of distant energetic muons made with an instrument of higher momentum resolution for comparison with the earlier data.

† Now at Royal Aircraft Establishment, Farnborough.
‡ Now at Rutland High School, Oakham.

It has also been possible with the visual detectors of the mark II spectrograph to measure accurately the lateral distribution function for muons of momentum greater than 1 GeV/c at distances as small as 30 m from the core showers initiated by 10^{17} eV primary particles and incident at zenith angles less than 30°.

The observational data are compared with the results of computer simulations of large showers made by Dixon *et al* (1973a).

2. Re-analysis of the data of the mark I spectrograph

The data from the mark I spectrograph which formed the basis of the momentum spectrum published by Machin *et al* (1970) have been re-analysed after substitution of EAS data derived from a more refined analysis procedure which has resulted in certain cases in more accurate core location estimations. The momentum spectra so obtained for muons, in showers incident at zenith angles less than 40°, do not differ significantly from those derived previously and are shown in figure 1. They are compared with the results of the recent computer simulations of proton initiated showers made by Dixon *et al* (1973a) and show good agreement at momenta up to 40 GeV/c.

3. The experimental arrangement of the mark II spectrograph

The improvement in momentum resolution has been obtained by the addition of 7500 small diameter (9 mm) high-pressure neon flash tubes and a diagram of the modified instrument is given by Earnshaw *et al* (1971). The small tubes produced a reduction in the RMS error of track location of about two over that available from the mark I spectrograph to a value of $\pm 0{\cdot}16°$, corresponding to a limit in momentum resolution in excess of 120 GeV/c. The many layers of small-diameter flash tubes which provide this location accuracy also form a useful muon density detector particularly in those regions close to the core where the muon density is large. This region is of importance and does not lend itself to easy measurement because of possible contamination from nuclear interacting particles in experiments using shielded scintillation detectors.

Of considerable importance to all the measurements reported here is the improvement in the precision of measured EAS parameters resulting from the incorporation into the Haverah Park 500 m array of three additional water Čerenkov detectors at distances of 150 m from the centre (see Andrews 1970); every shower analysed for the present measurement is based on at least 7 density samples from large area water Čerenkov detectors giving a precision of core location of ± 15 m for all distances in the range 30–500 m.

4. The momentum spectrum of muons at large core distances

The mark II spectrograph was constructed primarily to enable a check measurement to be made for the density of distant energetic muons in large EAS. Such muons are characterized in our spectrograph by undergoing angular deflection of less than $0{\cdot}36°$ (corresponding to a most probable momentum greater than 47 GeV/c). In the original instrument this corresponded to measurements in the region approaching the limit of momentum resolution; measurements with the improved spectrograph did not have this

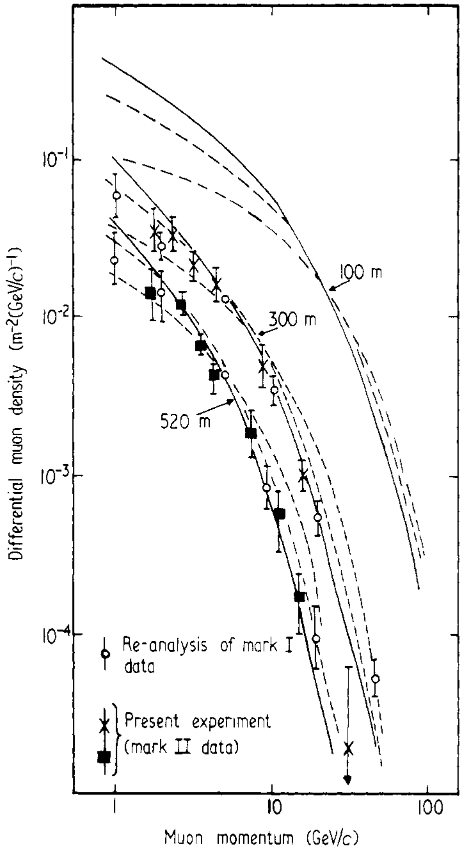

Figure 1. The differential momentum spectrum of muons in showers of primary particle energy about 10^{17} eV incident at zenith angles less than 40°. The results from the most recent analysis of data obtained with the original magnet spectrograph (mark I: Machin *et al* 1970) are compared with recent data for the modified instrument (mark II: present experiment) and recent simulation data (full curve, $\theta = 0°$; broken curve, $\theta = 30°$; chain curve, $\theta = 45°$).

limitation. In the earlier measurements using the mark I instrument the proportion of muons at distances of 250–350 m from the core having a measured angular deflection of less than 0·36° was $2{\cdot}78 \pm 0{\cdot}48\,\%$ of all muons recorded with deflection less than 16° (and so of momenta greater than 1 GeV/c). Of this proportion of apparently energetic muons approximately half were considered to be genuine and half were of low momentum but due to Coulomb scattering and errors in track location appeared to be energetic. This estimation was made on the basis of additional data available for each measured muon in the form of the lateral scatter suffered by the muon in the magnet iron. This scatter was estimated in the mid-plane of the magnet and the procedure has been reported by Machin *et al* (1970).

In the present measurement with the mark II spectrograph, if the original measurements had been correct, we would have expected all the genuine events to remain; however, as the scattering effect due to track fitting errors has been decreased in the mark II instrument, the proportion of low momentum particles scattered to appear as energetic particles decreased. For a spectrum of the shape previously quoted we would, for the mark II spectrograph, expect to observe 2·4 % of all events with angles of deflection less than 0·36°.

On the basis of data from 464 showers recorded with cores falling at distances 250–350 m from the detector in about two and a half years of operation of the mark II spectrograph we observe $1{\cdot}0^{+0\cdot7}_{-0\cdot45}$ % of all recorded muons to have deflections less than 0·36°, ie a little less than half the fraction predicted from our earlier work.

It is of interest to note that the expected proportion of energetic events, if the momentum spectrum of muons was as indicated from our recent simulations of proton initiated showers at the appropriate zenith angles, would be 1·0 %. The model used in the simulations is described by Dixon *et al* (1973a) and represents well many of the measurements made on showers at Haverah Park at zenith angles less than 40° and having energies in the region of 10^{17} eV.

The differential momentum distributions of all muons in core distance intervals in the range 250–600 m derived from the data from the mark II spectrograph are shown in figure 1.

5. Muon lateral structure function at small distances from the core of large EAS

5.1. Basic data

The density of muons of momentum greater than 1 GeV/c has been measured, using the flash-tube array of the mark II spectrograph as the detector and the magnet iron as the absorber, for over 200 showers when the zenith angle of the shower was less than 30° and the core distance was less than 100 m from the detector. Allowance has been made for the variation of sensitive detector area with zenith angle and azimuth angle, and the zenith angle dependence of the momentum cut-off imposed by the magnet iron and absorber thickness and of the geometrical acceptance of the system for muons of different momentum and sign.

It has been shown by Hillas (1972, private communication) and confirmed in our recent calculations (Dixon *et al* 1973a) that regardless of the mass of the primary particle, the ground parameter $\rho(500)$ (the deep water Čerenkov detector signal at a point 500 m from the shower core) measured at Haverah Park relates well with the primary particle energy, E_p, and this relation is also substantially independent of the interaction model assumed. We deduce that

$$\Delta_\mu(>1\ \mathrm{GeV}, 100\ \mathrm{m}) \propto \rho(500)^{0\cdot95\pm0\cdot06} \propto E_p^{0\cdot93\pm0\cdot06}. \qquad (1)$$

On the basis of these data and the data from model simulations we assume that the density at all distances less than 100 m varies with $\rho(500)$ as

$$\Delta_\mu(>1\ \mathrm{GeV}, r < 100\ \mathrm{m}) \propto \rho(500)^{0\cdot95}$$

and accordingly we adjust the value of the muon density for each recorded shower to that expected for an event with a $\rho(500)$ value of 0·33 m^{-2} (the median value of the present sample corresponding to an estimated value of the primary energy of about $1{\cdot}5\times10^{17}$ eV). The resulting lateral distribution at core distances of less than 100 m is shown in figure 2. Also shown are the data from the measurements of the density of muons at 300 m from the core for events with $\rho(500)$ chosen very close to the value of

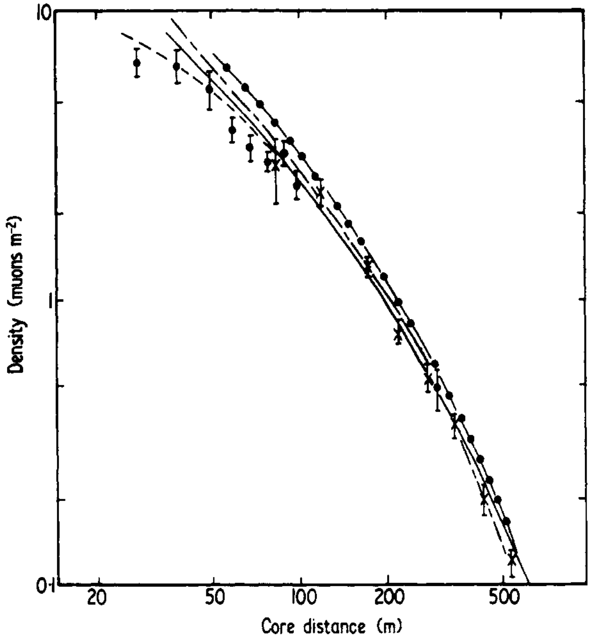

Figure 2. The lateral distribution of muons of energy greater than 1 GeV in large air showers (primary energy $\sim 1{\cdot}5 \times 10^{17}$ eV). The full curve is based upon the empirical representation given by Greisen (1960) and the broken curve indicates the effects of core location errors of ± 20 m. The chain and dotted curves represent the results from recent simulations of vertical proton and iron nucleus initiated showers respectively, which incorporate the effects of Coulomb scatter in the atmosphere and the geomagnetic field (Dixon *et al* 1973b). The simulation results are compared with the experimental results from the present experiment (♦) and those of Earnshaw (1968) (⨯).

$0{\cdot}33\ \mathrm{m}^{-1}$ which enables the earlier data of Earnshaw (1968) obtained with the mark I spectrograph and derived by a similar method to be included in the figure in the correct position with respect to the new data.

5.2. *Comparison with other data and model predictions*

It should be noted that in our earlier determinations of the lateral structure function of muons over a wide range of core distance (Earnshaw *et al* 1967) the data have been derived from measurements of muons in showers covering a large range of primary energy, between 10^{15} and 10^{18} eV, where a strong correlation exists between core distance and primary particle energy for each muon density measurement. In the present measurement there is a much smaller change in primary energy with core distance; a fact that arises from the ability to measure the large density of muons recorded at accurately estimated small distances from the shower core in the largest of the showers recorded by the Haverah Park 500 m array.

There is good agreement between the present data and an expression of the form

$$\Delta_\mu(>1\ \mathrm{GeV}, r, E_\mathrm{p}) = Kr^{-0{\cdot}75}\left(1+\frac{r}{320}\right)^{-2{\cdot}5} E_\mathrm{p}^{0{\cdot}93}\ \mathrm{m}^{-2}, \qquad (2)$$

where $K = 3\times10^{-6}$, E_p is in GeV and r, the perpendicular distance from the shower axis, is measured in metres. The full curve in figure 2 represents the empirical lateral structure function of the shape first suggested by Greisen (1960) and subsequently much used; the broken curve represents the distortion of such a structure function arising from a core location error of ±20 m, according to Watson (1973, private communication), which is appropriate to the Haverah Park air shower measurements.

The chain curve represents the lateral distribution function for muons in proton initiated showers and the dotted line shows that for an iron nucleus initiated shower according to the simulations of Dixon *et al* (1973b). The calculations are made for vertically incident showers and include detailed treatment for the effects of the Coulomb scattering of the muons in the atmosphere and the influence of the geomagnetic field.

6. Conclusions

The average lateral distribution of muons of momentum in excess of 1 GeV/c in showers initiated by primary particles of energy about 10^{17} eV is in agreement with earlier measurements as typified by the lateral structure function suggested by Greisen (1960), when allowance is made for the effects of core location errors.

We find no evidence for the flattening of the lateral distribution function at core distances less than 100 m noted by McCusker (1972, private communication). There is satisfactory agreement between our measurements and data from our computer simulations of either proton or iron nucleus initiated showers. (The simulation data are for showers of primary energy chosen to give similar values of the ground parameter at the Haverah Park array; however, the present comparison should be confined to the shapes of the lateral distributions since differences in absolute densities of the magnitude indicated here may arise from the choice of the appropriate primary energy in the simulations.)

The data available from two and a half years of operation of the mark II spectrograph for the momentum spectrum of muons of momentum 20–50 GeV/c at core distances of 250–350 m do not confirm our earlier measurements. We note a large discrepancy in densities at the highest momenta but have been unable at present to determine the cause. The possible causes of the large number of energetic particles recorded at large core distances in the earlier work are:

(i) the muons were not of high energy but appeared to be as a consequence of the proximity of the measurement to the limit of momentum resolution spectrograph;

(ii) the recorded muons were not distant from the shower core but appeared to be so as a result of the mislocation of a small proportion of the cores in the early shower analyses.

It must however be emphasized that we can find no reason at present to accept either one or both of these possible explanations.

We note that the data from our recent simulations for proton induced showers in the zenith angle range 0–40° agree well with our new observations to momenta as high as about 40 GeV/c. It is not possible on the basis of the present data to specify the spectrum at higher momenta as a consequence of the limited sample of data.

We note that the recent computer simulations of large EAS made by Dixon *et al* (1973b) indicate that we should not expect any useful sensitivity of the shower parameters described here to the atomic mass number of the primary particle when measurements are averaged over many showers.

Acknowledgments

We are indebted to Professor G D Rochester FRS and Professor A W Wolfendale for their interest in this work and Professor J G Wilson and colleagues in the University of Leeds for their efforts in providing the shower analyses.

The work was supported by a grant from the Science Research Council.

References

Andrews D 1970 *PhD Thesis* University of Leeds

Dixon H E *et al* 1973a *Proc. 13th Int. Conf. on Cosmic Rays, Denver* vol 4 (Denver: University of Denver) pp 2556–61

Dixon H E, Stephenson W and Turver K E 1973b unpublished

Earnshaw J C 1968 *PhD Thesis* University of Durham

Earnshaw J C *et al* 1967 *Proc. Phys. Soc* **90** 91–108

Earnshaw J C *et al* 1971 *Proc. 12th Int. Conf. on Cosmic Rays, Hobart* vol 3 (Hobart: University of Tasmania) pp 1081–5

Earnshaw J C *et al* 1973 *J. Phys.* A: *Math., Nucl. Gen.* **6** 1244–61

Greisen K 1960 *Ann. Rev. Nucl. Sci.* **10** 1–60

Machin A C *et al* 1970 *Proc. 11th Int. Conf. on Cosmic Rays, Budapest* vol 3 (Budapest: Akademiai Kiado) pp 579–84

Orford K J *et al* 1968 *Can. J. Phys* **46** S119–22