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1969 J. Phys. A: Gen. Phys. 2 365

(http://iopscience.iop.org/0022-3689/2/3/016)

J. PHYS. A (GEN. PHYS.), 1969, SER. 2, VOL. 2. PRINTED IN GREAT BRITAIN

Observations of multiple muons in cosmic rays at a variety of zenith angles

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MS. received 11*th December* 1968

Abstract. A large vertical array of muon detectors has been used to measure the frequency of multiple muons from extensive air showers as a function of zenith angle over the range 30°–85°. The experimental data have been compared with the predictions of the theory developed by de Beer *et al.* in 1969; accepting the values of the parameters used in this theory it is concluded that there is no evidence for a large increase in the relative flux of heavy nuclei in the energy range 10^{15}–10^{17} ev.

If all the other parameters but the mean transverse momentum $\langle p_T \rangle$ are assumed to be known, the data suggest a mean value of $\langle p_T \rangle$ increasing from 0·37 GeV/c to 0·44 GeV/c as the interaction energy increases from 200 to 3900 GeV.

1. Introduction

The present paper concerns an experiment to determine the density spectrum of cosmic ray muons in extensive air showers incident at a variety of angles to the vertical and gives a comparison of the experimental results with predictions based on the theory described in the accompanying paper by de Beer *et al.* (1969, to be referred to as III). A preliminary account of the work has been given by Alexander *et al.* (1968); since that work was reported more data have been accumulated and a more detailed comparison with the theory has been made. Such an analysis was clearly dictated by the equivocal results found in that study (one analysis suggested a mean transverse momentum of 0·4 GeV/c whereas another suggested 0·8 GeV/c).

2. Experimental apparatus

The main feature of the apparatus is a comparatively large detecting area having a high well-defined efficiency and capable of giving reasonable directional resolution.

The apparatus, shown in figure 1, comprises a vertical area of 33·9 m^2 incorporating twelve trays of horizontally arranged neon flash tubes. It is located in the laboratory at Durham, near sea level, and the normal to the array makes an angle of 27° to the east of the magnetic meridian.

Each tray contains four vertical layers of tubes, the tubes being 2·5 m long and 1·8 cm in diameter, and the fronts of all the tubes are photographed by a single camera through a mirror system.

The selection system utilizes two counter telescopes, each comprising two 1 m^2 plastic scintillation counters, between which are sandwiched 3·6 radiation lengths of iron and four layers of flash tubes. The telescopes are mounted with their axes perpendicular to the plane of the main array and in such a position that particles traversing the telescopes also pass through trays 1 and 10. A 7·5 cm layer of barytes concrete is located between each telescope and the array trays, and a further 15 cm layer extends over the top of the telescope. The purpose of this is to reduce the triggering of the telescopes by electron showers. The counters at the northern end of each telescope are 15 cm higher than those at the southern end in order to bias the system towards particles from the North.

On the south side of each telescope a tray of vertical flash tubes is located whose function is to give an estimate of the azimuth of the detected particles.

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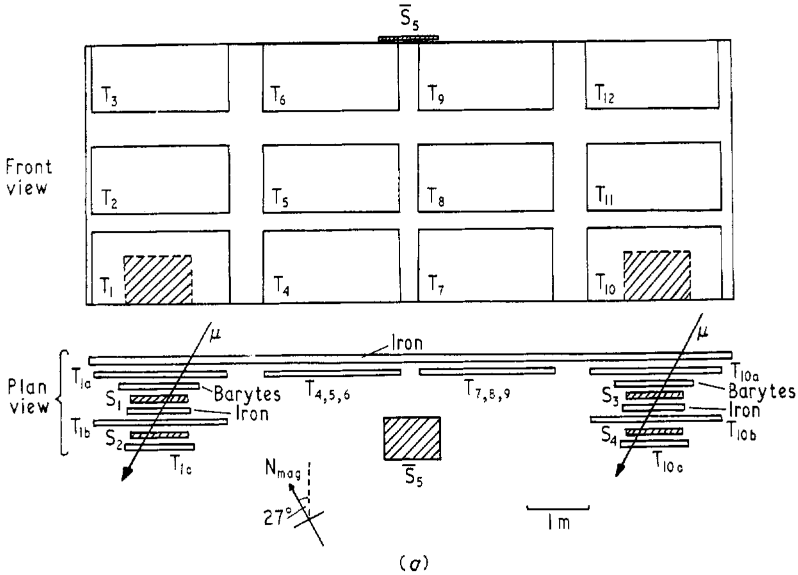

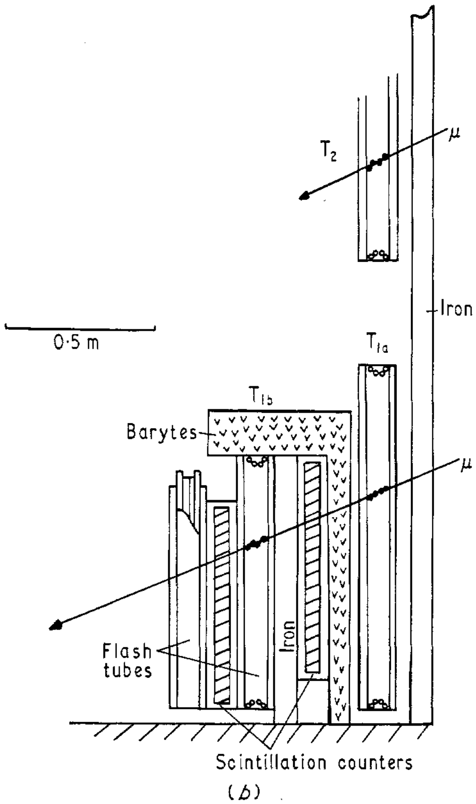

Figure 1. The experimental arrangement. S_1–S_5 are 1 m² scintillation counters and T_1–T_{12} are trays of flash tubes. (a) Front and plan views. (b) Detail of a telescope.

In addition to the absorber in the telescope, the whole of the apparatus is shielded on its northern side by 4·5 radiation lengths of iron. Particles passing through the telescopes have passed through a total of 9·5 radiation lengths of absorber and are presumed to be muons. Accompanying particles which pass through the other flash tube trays have only penetrated 4·5 radiation lengths (for near horizontal incidence) and there is thus a significant *a priori* chance of their being electrons. However, at these very large zenith angles the frequency of energetic electrons is low; it is only at angles less than about 50° where there is a high frequency of electrons and there the greater (oblique) thickness of absorber reduces the probability of an electron not being identified as such to neglegible proportions.

An anti-coincidence counter of area 1 m^2 (S_5 in figure 1) is mounted above the array to assist further in the rejection of extensive air showers which arrive at small zenith angles and, correspondingly, contain a large electron component.

The selection system, comprising the twofold telescopes (S_1S_2), (S_3S_4) with S_5 in anti-coincidence, is therefore designed to select showers with at least two muons which have come from the North and passed through the iron filter before traversing the telescopes. Of the total counting rate of about 2·5 h^{-1} about 0·5 h^{-1} are of the desired type; the remainder comprise similar showers from the South and weak extensive air showers at small zenith angles which have missed the anti-coincidence counter.

3. Basic data and experimental checks

3.1. *Efficiency of detection systems*

3.1.1. *The scintillator telescope.* High efficiency of the scintillation counters is ensured by setting the discrimination level well below the foot of the single-particle pulse height distribution and a 100 ns resolving time on the fourfold coincidence system reduces the rate of noise triggers to negligible proportions. A regular check is made of the counters by means of a multi-channel pulse height analyser. A further guarantee of the efficiencies of the telescopes is a regular check on the rate of single particles through them (22 s^{-1}). A check on the absolute efficiency of the apparatus has been made by triggering the flash tubes in the telescopes on single particles, and obtaining the angular distribution. This agrees well, both in shape and magnitude with theoretical prediction based on the known angular variation of single muons and the acceptance of the telescopes.

3.1.2. *The flash tubes.* The measured flash tube efficiency for a single layer of tubes is 88% (the bulk of the inefficiency arising from the finite thickness of the glass walls) and the probability of a muon traversing a tray of tubes, containing four layers, without producing at least two flashed tubes is less than about 3%.

3.2. *Selection of events*

Events are selected from the film that show at least one 'North' track in at least one flash-tube tray in each telescope. The projected zenith angle of each triggering particle is then measured to within $\pm\frac{1}{2}°$ using a scale diagram of the system and those events in which the angle between the tracks is greater than 4° are rejected. In the majority of the events the tracks intersect the azimuthal trays and the azimuthal angle is measured (this measurement is only used to give a check on the validity of the assumed azimuthal variation of the events).

The events thus selected are divided into 5° cells in projected zenith angle, as measured in the telescopes, and those tracks in the main array which are within $\pm 10°$ of the triggering particles (i.e. are parallel within the angular resolution of the main trays) are added to give the total number of muons (termed the multiplicity) of each event. In this way the variation of rate with both zenith angle and multiplicity is determined.

3.3. *Frequency of events*

The data refer to a running time of 2218 hours, for which the aperture, integrated over all azimuthal angles, was 0·16 steradian per 5° of projected zenith angle. Table 1 gives the frequencies of the various multiplicities divided according to projected zenith angle.

Table 1. Basic data on multiple muons

Multiplicity	No. of events per 5° range of zenith centred about angle stated												Total
	30°	35°	40°	45°	50°	55°	60°	65°	70°	75°	80°	85°	
2	42	60	103	79	87	68	50	34	20	4	1	4	552
3–4	15	20	40	46	29	14	14	9	5	2	—	—	194
5–8	2	4	8	10	12	11	8	8	2	1	—	—	66
9–16	2	4	5	7	5	4	2	1	—	—	—	—	30
17–32	—	—	—	2	2	3	1	—	1	—	—	—	9
33–64	—	—	1	—	—	—	1	—	—	—	—	—	2

4. Comparison with theory

4.1. *Angular distribution for primary protons and* $\langle p_T \rangle = 0{\cdot}4$ GeV/*c*

The theoretical density spectra given in III have been used, together with the geometrical properties of the apparatus, to calculate the expected frequencies of multiple muons as a function of projected zenith angle, with the results given in figure 2. Each point on the

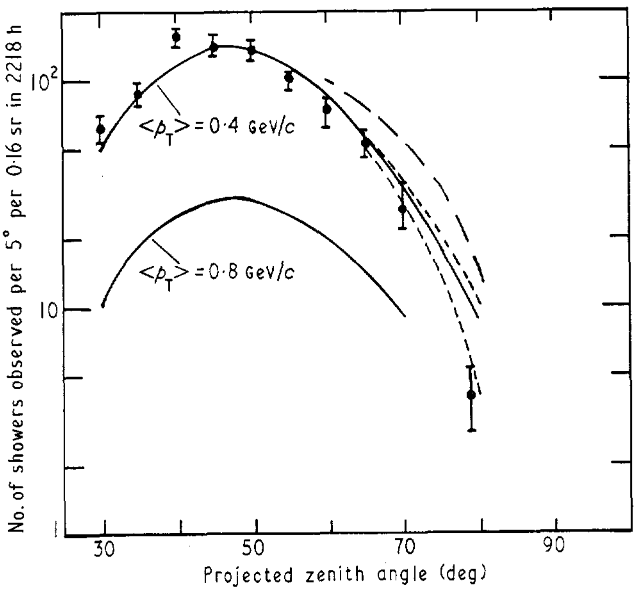

Figure 2. Frequency distribution of multiple muons plotted against projected zenith angle. The theoretical curves refer to two values of $\langle p_T \rangle$: 0·4 and 0·8 GeV/*c*. – – – No geomagnetic correction, --- indicate range of uncertainty, ——— best estimate.

line in the figure is derived in the following way. Combination of the differential density spectrum for a given zenith angle with the trigger probability derived from the geometry of the detectors gives the effective density spectrum. This is then combined with the Poisson probability of observing a given number of additional muons in the flash-tube area to give a differential density spectrum of showers producing a given multiplicity at a given zenith angle. A summation over density gives the predicted total rate and multiplication by the running time and acceptance of the apparatus (allowing for the range of azimuthal angles) gives the predicted number in the angular range in question.

The density spectra used are based on an assumed value for the mean transverse momentum $\langle p_T \rangle$ of 0·4 GeV/*c* and a primary spectrum of pure proton composition above 10^{15} eV of such an intensity as to give consistency with the size spectrum of near vertical extensive air showers (spectrum A of III).

It should be stressed that the comparison in figure 2 is direct and that no normalization has taken place. At the largest zenith angles, $\theta \gtrsim 70°$, however, there is uncertainty in the magnitude of correction for the effect of geomagnetic deflection, and the theoretical prediction is correspondingly imprecise.

It is clear from figure 2 that there is reasonable agreement with expectation so that the particular combination of parameters used in the theoretical analysis is at least a possible one.

4.2. *Sensitivity to changes in mass composition and* $\langle p_T \rangle$

In order to study the variation of these two important parameters with primary particle energy, the theoretical analysis has been used to find the median primary energy for each cell of multiplicity and angle, and the data have been grouped in order of increasing primary energy. This increase is due largely to increased multiplicity rather than increased zenith angle.

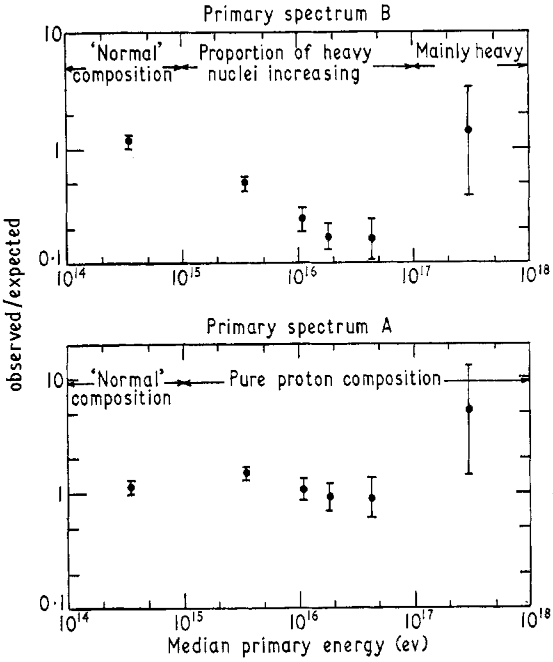

Figure 3. The ratio of observed to expected frequencies of multiple muons as a function of the median primary energy.

Figure 3 shows better agreement with the assumption of spectrum A of III than for the modulated primary spectrum, that is one with an increasing fraction of heavy nuclei above 10^{15} ev, at least to about 10^{17} ev, and, indeed, if the values for all the other parameters were known to be exact a firm conclusion could be made. However, this is obviously not the case and, in particular, the sensitivity to $\langle p_T \rangle$ has been stressed (see III).

In an attempt to disentangle the effects of the two parameters the results have been examined in a different way. The value of $\langle p_T \rangle$ required to give agreement between theory and experiment has been calculated as a function of the mean energy of the interactions from which the parents of the detected muons come. The interactions in question will not be those of the primary particles but rather of pions in later generations (mean energy E_π^*). Figure 4 shows $\langle p_T \rangle$ plotted against E_π^* for events having a multiplicity of at least 2. Here, the increase in E_π^* comes from increasing zenith angle, low interaction energies contributing little because of the loss of the ensuing low-energy muons by way of μ–e decay and ionization loss. In the figure, points derived from the angular data having

$E_\pi^* > 1500$ GeV correspond to zenith angles greater than 60°. The normal primary composition has been adopted because the median primary energy is only about 3×10^{14} ev. At this stage it can be remarked that the values of $\langle p_T \rangle$ are close to those found in studies of jets in nuclear emulsions (see de Beer *et al.* 1968).

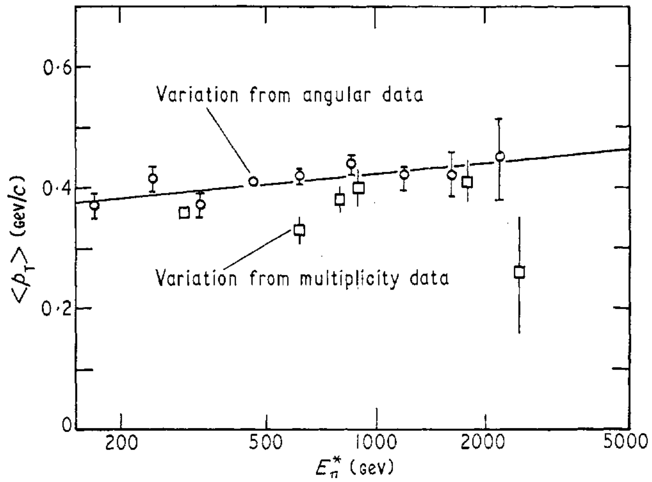

Figure 4. Mean transverse momentum plotted against mean pion energy, assuming spectrum A.

The data have also been analysed with respect to the variation of frequency with multiplicity without regard to inclination ('multiplicity analysis').

As the multiplicity increases the mean muon energy does likewise and with it the corresponding value of E_π^*. However, unlike the previous case there is a considerable increase in the median primary energy so that in principle, at least, by comparing the variation of $\langle p_T \rangle$ with E_π^* for the two situations (increasing zenith angle and increasing multiplicity) it is possible to distinguish between the two primary spectra.

The variation of $\langle p_T \rangle$ with E_π^* found from the multiplicity analysis is also shown in figure 4, the primary spectrum adopted being that denoted 'spectrum A'. It is clear that the two variations are consistent, again suggesting that A is the preferred spectrum.

5. Comparison with the results of other workers

Other experiments carried out to study multiple muons as a function of zenith angle are those of Sekido *et al.* (1966) and Parker (1967). In so far as the threshold energies are different from those in the present experiment a direct comparison with the present experimental data is not meaningful. Instead, comparison has been made with theory, allowance being made in the computations for the different threshold energies.

5.1. *Sekido et al.* (1966)

These workers used two air Čerenkov counters, each having an effective area of 10 m^2 and viewing a solid angle of 0·05 steradians. The minimum muon energy required for triggering was 10 GeV. The variation of frequency with zenith angle is shown in figure 5, where comparison is made with the frequency expected from application of the theory described in III with $\langle p_T \rangle = 0{\cdot}4$ GeV/c and the appropriate minimum muon energy. A geomagnetic correction has been estimated, as indicated.

In an experiment of this type the derivation of accurate absolute frequencies is a matter of some difficulty in view of detection efficiency problems; the frequencies plotted in the figure are those given by Sekido (1967, private communication) scaled up by a factor 1·4 to allow for the latest efficiency estimate, this factor also having been estimated from unpublished data of Sekido.

Comparison of the results with expectation shows rather good agreement, except at an angle of 75°, but in view of the difficulty in making an accurate correction for geomagnetic deflection the discrepancy here is not regarded as serious.

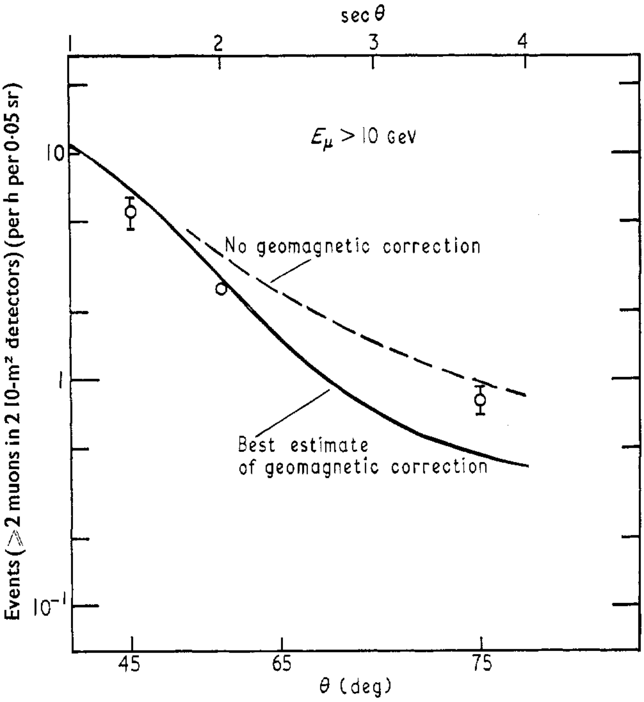

Figure 5. Comparison with results of Sekido *et al.* (1966, 1967, private communication). The muon energy threshold is 10 GeV.

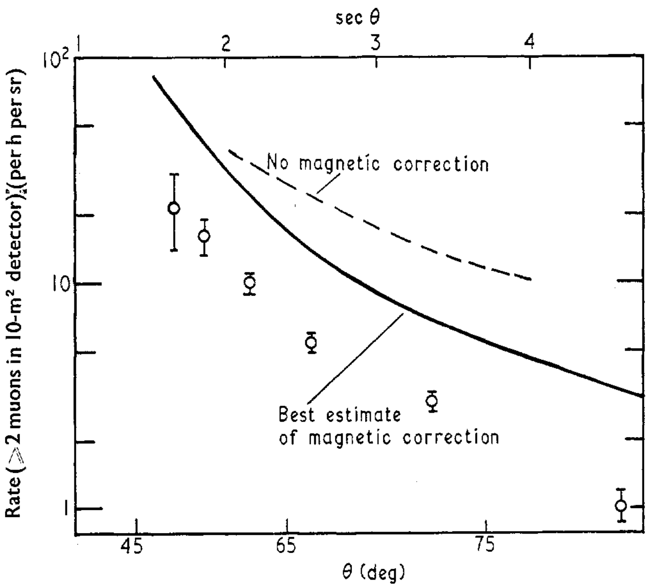

Figure 6. Comparison with results of Parker (1967). The muon energy threshold is 2 GeV.

5.2. *Parker* (1967)

The prototype of the Utah underground neutrino detector was operated at ground level and 1200 events were detected which consisted of two, or more, nearly parallel muons with zenith angles between 45° and 90°. A preliminary report on the measurements, which are statistically the most precise to date, has been given by Parker (1967, and 1967, private communication). The threshold muon energy is approximately 2 GeV and the geomagnetic conditions are rather close to those pertaining in Durham.

Figure 6 shows the experimental data and a comparison of the predicted variation of rate with angle using the theory given in III. Although the shape of the variation of rate with angle is seen to be in good agreement with expectation, the experimental points are low by a factor of approximately 2. Inevitably with the types of detectors used (Čerenkov and sonic spark chambers) and the rather complex geometry there is some uncertainty in the magnitude of the efficiency of the system, and this may be responsible for some of the discrepancy. Perhaps more important are inaccuracies in our calculation of the expected frequencies, using the predicted density spectrum and the geometry of the system. Taken together it is just possible that there is in fact no inconsistency between theory and experiment.

If, however, the discrepancy is real, and it is the data of Sekido *et al.* and the present work (or our analysis of these data) which are incorrect then, assuming the normal primary mass composition, the value of $\langle p_T \rangle$ needed to restore agreement is 0·5 GeV/*c*. The assumption about the mass composition is valid because the great majority of the events have multiplicity 2 and for these the median primary energy is less than 10^{15} eV, where it is thought that the mass composition is known.

6. Discussion and conclusions

6.1. *The mean transverse momentum*

The results reported show that if the other model parameters have been chosen correctly the mean transverse momentum of the pion secondaries increases slowly from about 0·37 GeV/*c* at an interaction energy of 200 GeV to 0·44 GeV/*c* at 3000 GeV. Such a variation is in good agreement with observations on jets in nuclear emulsions.

Of the parameters used in the calculations the multiplicity law for the secondary pions is probably the most uncertain. If we write the variation of multiplicity with primary energy E as $n \propto E^S$, the variation of derived $\langle p_T \rangle$ with S can be examined qualitatively. For $S > 0{\cdot}25$ there will be an increase in $\langle p_T \rangle$ because the primary intensity needed to give the same sea-level-size spectrum will be higher and this, taken together with the greater yield of muons, will predict high sea-level frequencies of multiple muons (see I for the relationships for $S = 0{\cdot}5$). Conversely, for $S < 0{\cdot}25$, $\langle p_T \rangle$ will be somewhat lower.

6.2. *The primary mass composition*

It is clear from figures 3 and 4 that the present work does not support the view commonly put forward that there is a preponderance of heavy primaries in the energy range 10^{15}–10^{17} eV but rather suggests a nearly pure proton composition in this region.

Reference to the heavy primary hypothesis has already been made in III where it was stated that other studies which supported this hypothesis are in our view inconclusive. Recent work, which at first sight is inconsistent with the primary proton hypothesis, is the recent measurements of the lateral distribution of high-energy muons in the Haverah Park array (Earnshaw *et al.* 1967). The data were first interpreted in terms of an increase in the transverse momentum of the secondary pions (Earnshaw *et al.* 1968a, b, de Beer *et al.* 1968) but more recently Orford and Turver (1968) have put forward another explanation—that the results give evidence for heavy primaries. However, the primary energy in question is in the region of 2×10^{17} eV where the present data are imprecise and where, in fact, there is better agreement with the heavy primary hypothesis (figure 3), so that inconsistency does not arise.

Acknowledgments

The Science Research Council is thanked for the provision of a research grant to support this work and the award of a Research Fellowship to I.W.R.

The authors wish to thank Professor G. D. Rochester for his interest in the work and Dr. A. O. Sanni, Dr. B. Holyoak, Mr. C. Adcock, Mr. D. Alexander and Dr. J. Wdowczyk and thanked for their help.

We are particularly grateful to Professor Y. Sekido and Dr. J. L. Parker for very helpful discussions and correspondence.

References

Alexander, D., Holyoak, B., Thompson, M. G., and Turner, M. J. L., 1968, *Proc. 10th Int. Conf. on Cosmic Rays, Calgary*, 1967 (*Can. J. Phys.*, **46**, S273–7).

de Beer, J. F., *et al.*, 1968, *Proc. 10th Int. Conf. on Cosmic Rays, Calgary*, 1967 (*Can. J. Phys.*, **46,** S185–8).

—— 1969, *J. Phys.* A (*Gen. Phys.*), [2], **2,** 354–64.

Earnshaw, J. C., Maslin, G. C., and Turver, K. E., 1968 a, *Proc. 10th Int. Conf. on Cosmic Rays, Calgary*, 1967 (*Can. J. Phys.*, **46,** S115–8).

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

Earnshaw, J. C., *et al.*, 1968 b, *Proc. 10th Int. Conf. on Cosmic Rays, Calgary*, 1967 (*Can. J. Phys.*), **46,** S122–6.

Orford, K. J., and Turver, K. E., 1968, *Nature, Lond.*, **219,** 706–8.

Parker, J. L., 1967, *Ph.D. Thesis*, University of Utah.

Sekido, Y., *et al.*, 1966, *Proc. 9th Int. Conf. on Cosmic Rays, London*, 1965, Vol. 2 (London: Institute of Physics and Physical Society), pp. 632–4.