A study of muons deep underground. I. Angular distribution and vertical intensity

1969 J. Phys. A: Gen. Phys. 2 639

(http://iopscience.iop.org/0022-3689/2/6/004)

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

A study of muons deep underground: I. Angular distribution and vertical intensity†

C. T. STOCKEL

Department of Physics, Northern Polytechnic, London

MS. received 21*st April* 1969, *in revised form* 6*th June* 1969

Abstract. The angular distribution and vertical intensity of cosmic-ray muons have been measured at depths of 71·6, 734, 1068 and 2235 hg cm^{-2} of standard rock. The angular distribution was fitted by a law of the form $I_\theta = I_v \cos^n \theta$ and values of the exponent n were found to be 1·8 ±0·1, 2·1 ±0·1, 2·3 ±0·1 and 3·6 ±0·2 respectively. The corresponding vertical intensities were found to be (5·00 ±0·17) × 10^{-4}, (3·12 ±0·15) × 10^{-6}, (1·03 ±0·04) × 10^{-6} and (9·7 ±0·5) × 10^{-8} cm^{-2} s^{-1} sr^{-1} respectively.

From a survey of all previous measurements, best estimates of the n–depth and intensity–depth curves are derived. The results are explicable entirely in terms of pion and kaon decay for the origin of the muons and do not agree with the direct muon production hypothesis advanced by Bergeson *et al.* in 1967.

1. Introduction

Reviews of previous experiments have been given by George (1952), Barrett *et al.* (1952) and Menon and Ramana Murthy (1967). One of the major problems in this work arises from the need to detect a small flux of cosmic rays in the presence of a vastly greater flux of background gamma radiation. Several of the earlier experiments were unsuccessful because it was not realized that, unless suitable precautions were taken, gamma rays could give rise to twofold and threefold coincidences in unshielded cosmic-ray telescopes. In the present experiment gamma-ray coincidences were completely excluded by means of pulse-height analysis of the output from a scintillation counter operated in a threefold coincidence arrangement.

A further difficulty arises from the nature of the energy losses for muons traversing absorbers. A simple correction of underground depths to units of metres water equivalent is inadequate as it fails to allow for the effect of the various values of Z/A and Z^2/A on the energy losses and hence on the range of the muons. This was first appreciated by Mando and Ronchi (1952), who introduced the term hectogram per square centimetre of standard rock (hg cm^{-2}). It is convenient to follow Menon and Ramana Murthy (1967) and adopt a slightly different definition of this unit from that of Mando and Ronchi, so that standard rock is now defined as having a density of 2·65 g cm^{-3}, mean Z/A of 0·5 and mean Z^2/A of 5·5. All measurements of depth will be quoted in these units and measured relative to the top of the atmosphere.

2. Experimental method

The apparatus shown in figure 1 consisted of a combined scintillation counter and Geiger counter cosmic-ray telescope, together with battery-operated, transistorized electronic circuits and magnetic tape recording equipment. The scintillation counter comprised a 90 cm × 40 cm × 4 cm block of NE 102 plastic scintillator, cemented between two 10 cm × 40 cm × 4 cm Perspex light guides, and four E.M.I. type 9584B 2 in diameter photomultipliers, two of which viewed the phosphor through each light guide. The scintillation counter was mounted between two trays, each of twenty-three Geiger counters, which were of the organic quenched type with carbon film cathodes and were 43 cm long and of 3·7 cm external diameter.

The electronic circuits may be considered in four groups: control circuits, pulse-height analyser, hodoscope and power circuits. The elements of the first three groups are shown

---

† This work formed part of a Ph.D. thesis which has been accepted by the University of London.

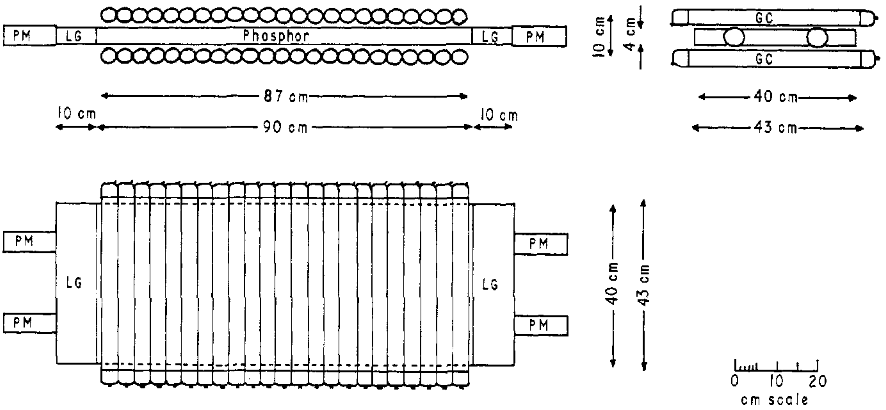

Figure 1. The cosmic-ray telescope: LG, light guide; PM, photomultiplier; GC, Geiger counter.

as a block diagram in figure 2. Two outputs were taken from each photomultiplier and from each Geiger counter, the first of each being connected to the control circuits. A fast coincidence of 100 ns resolving time was demanded from the photomultipliers to avoid spurious events, and the output from the fast coincidence circuit was shaped to a standard length of 500 ns before being led to the slow coincidence circuit. The other two inputs to this circuit were derived from the two trays of Geiger counters by means of two 23 channel mixing and pulse-shaping circuits, one for each tray. These circuits produced a standard length pulse whenever one or more Geiger counters were discharged in a tray. By suitable biasing of this coincidence circuit spurious events from background gamma radiation were eliminated. The output from the slow coincidence circuit was connected to the master circuit, a blocking oscillator, which produced a standard pulse of 63 μs duration used to gate the pulse-height analyser, and, after shortening to 10 μs, the hodoscope also. Provision was made to interpose a scaler, of six binary stages, between the slow coincidence circuit and the master circuit. The operation of this scaler could be adjusted so as to divide the master pulse rate by a factor varying from 2 to 64 to ease the problem of data collection at high counting rates.

The pulses from the scintillation counter were analysed by means of a 64 channel logarithmic analyser based on that of Barton and Crispin (1962), but operating at a frequency of 1 MHz. The analyser had a channel width of 1·00 ± 0·02 dB/channel. The input to the analyser binary register was gated by the master circuit to ensure that it was only set up by genuine events; the time of 63 μs was chosen to prevent the possible overflow of the binary register in the analyser by a very large pulse. The pulse-height channel

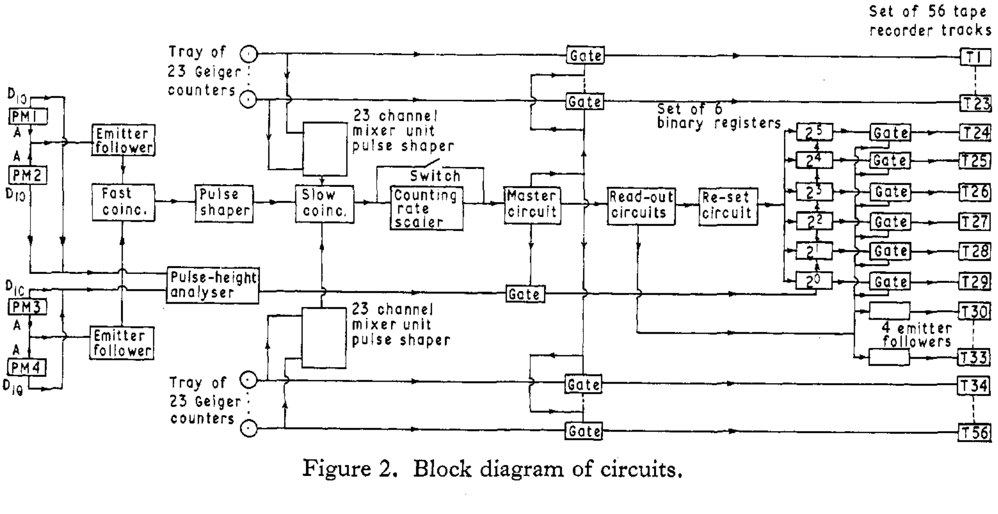

Figure 2. Block diagram of circuits.

number was read out from the register as a group of six binary digits to the magnetic tape data recorder.

A positive indication of the individual Geiger counters discharged in each event was given by the hodoscope circuit, in which the second output from each counter was connected to the magnetic tape recorder through a gated emitter–follower circuit.

The data were recorded on a 56 track magnetic tape recorder with simultaneous recording across the width of $\frac{1}{4}$ in wide tape (Barton and Stockel 1964); 46 tracks were used for the Geiger counter hodoscope, 6 for the pulse-height analyser channel number and 4 for event position markers, derived from the read-out circuit. The recorder was driven by a 6 v d.c. motor, the speed of which was stabilized by a built-in governor. Two different motors of this type were used. The slower motor ran at $\frac{1}{4}$ rev h^{-1}, giving a tape speed of 5 cm h^{-1}, and was used for the deep underground measurements. For measurements on the surface and at the shallowest depth the faster motor, 4 rev h^{-1}, was used, together with the scaler previously mentioned, so that the more frequent events could be recorded without overlapping on the tape. Sufficient tape was included to allow for 6 weeks' continuous operation with the slower motor. The data were recovered from the tape by making the recorded pattern visible with an iron powder technique and identifying each track relative to the fixed-event position markers.

The complete apparatus was tested regularly on the surface to ensure that neither the pulse-height analyser nor the hodoscope was being triggered by spurious events and that the calibration of the pulse-height analyser remained constant. The performance of the scintillation counter was checked by measuring the mode pulse height and resolution of the cosmic-ray peak. Together with the total counting rate, these values remained constant, within experimental error, throughout the entire experiment. The uniformity of the scintillation counter was measured at the greatest depth. The maximum non-uniformity was found to be $14 \pm 1\%$, and the corresponding resolution of the cosmic-ray peak for the whole scintillator was $49 \pm 2\%$.

Measurements were made at four underground locations. The depth of the shallowest site, the Holborn Underground Laboratory, is known to be $61{\cdot}3 \pm 1{\cdot}2$ m.w.e. below sea level (Hunter 1961). This is equivalent to a depth of $71{\cdot}6 \pm 1{\cdot}2$ hg cm^{-2} of standard rock below the top of the atmosphere. The depths of the other sites, at Tilmanstone Colliery, Kent, were determined in the following manner. A detailed geological section through the mine and plans of the shafts were provided at the colliery, from which the actual depths of the locations below the surface were found correct to the nearest foot. These depths were converted into units of m.w.e. of the actual rock using the *in situ* density values determined by Bullerwell (1954), who carried out a gravity survey in the shafts of this colliery. These values, which take the surface irregularities and mine workings into account, are now known to be correct to $\pm 1\%$ (Bullerwell 1965, private communication). A similar conversion was also made independently on the basis of a gravity survey carried out at Snowdown Colliery, which is 2·5 miles from Tilmanstone and in a very similar geological succession (Domzalski 1954). The validity of this was checked from measurements of the density of rock samples taken when the shafts were sunk (Bloodworth 1965, private communication). From these methods an estimate of the depths in m.w.e. was made with an accuracy of the order of $\frac{1}{2}$ to 1%. The depths were then corrected to units of hg cm^{-2} of standard rock below the top of the atmosphere using the method of Menon and Ramana Murthy (1967). The values that were finally obtained are shown in table 1.

Table 1. Depths of experimental sites

Tilmanstone Colliery location	Depth below surface (ft)	Depth below top of atmosphere (m.w.e.)	Corrected depth below top of atmosphere (hg cm^{-2})
pumping station	1140	726 ± 10	734 ± 10
No. 1 seam	1560	1058 ± 10	1068 ± 10
No. 6 seam	3020	2222 ± 10	2235 ± 12

3. Experimental results

The experimental programme was divided into a number of runs, for each of which the following data were recorded: the duration, the total number of events observed and, for each event, the scintillation counter pulse height and the identity of each Geiger counter that was discharged. Runs on the surface were taken between each underground run solely for the purpose of testing the apparatus and checking the constancy of its performance throughout the programme; no attempt was made to measure the muon flux at sea level. At the Holborn Underground Laboratory the scaler in the master circuit was connected so as to divide the counting rate by a factor of 4. This scaler was not used in the runs at greater depths. At Tilmanstone Colliery one run was taken with the apparatus resting in a horizontal position on the floor of the gallery at each depth. Care was taken to ensure that the locations chosen were at least several metres from any mine shafts. At the greatest depth an additional run was taken with the apparatus suspended close to the roof of the gallery. The significance of this run, which was taken as a check on the lateral spread of showers emerging from the rock, is discussed later.

An example of the pulse-height analyser record is shown in figure 3. The Geiger counter hodoscope records were examined event by event for each run, and the individual events were divided into two groups. The first group, single events, comprised those events which could be reasonably attributed to a single muon passing through the telescope, and the second group, multiple events, comprised the remaining events in which the muon was accompanied by shower particles. A summary of these results is shown in table 2.

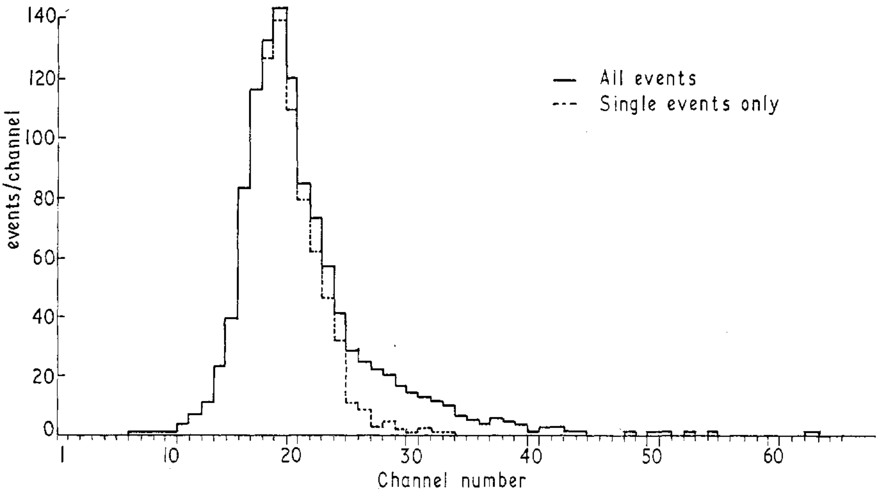

Figure 3. Pulse height histograms at depth 2235 hg cm^{-2} (floor).

Table 2. Summary of underground results

Depth (hg cm^{-2})	Duration (h)	Events	Counting rate (events s^{-1})	Single events (%)	Multiple events (%)
$71{\cdot}6 \pm 1{\cdot}2$	1·033	2062†	$2{\cdot}217 \pm 0{\cdot}025$	93	7
734 ± 10	24·2	1142	$(1{\cdot}31 \pm 0{\cdot}04) \times 10^{-2}$	89	11
1068 ± 10	143·8	2118	$(4{\cdot}08 \pm 0{\cdot}09) \times 10^{-3}$	86	14
2235 ± 12 (floor)	1006	1123	$(3{\cdot}10 \pm 0{\cdot}09) \times 10^{-4}$	82	18
2235 ± 12 (roof)	840	916	$(3{\cdot}04 \pm 0{\cdot}10) \times 10^{-4}$	84	16

† Using the scaler which divided the counting rate by 4.

For each run in turn, the trajectory of each single event was plotted on a full-scale diagram of the telescope. The maximum and minimum possible projected zenith angles were measured for each event and the arithmetic mean was taken as the effective projected zenith angle. These angles were then grouped into successive intervals of 8° and the resulting distribution for each depth shown in table 3.

Table 3. Uncorrected angular distributions

Angular interval (deg)	Events observed at depths (hg cm^{-2})				
	71·6	734	1068	2235 (floor)	2235 (roof)
$0 \leqslant \theta < 8$	395	230	416	243	198
$8 \leqslant \theta < 16$	374	195	373	212	180
$16 \leqslant \theta < 24$	331	172	334	179	146
$24 \leqslant \theta < 32$	269	144	264	131	106
$32 \leqslant \theta < 40$	216	87	193	82	67
$40 \leqslant \theta < 48$	134	69	124	47	40
$48 \leqslant \theta < 56$	94	38	71	16	21
$56 \leqslant \theta < 64$	46	20	31	5	7
$64 \leqslant \theta < 72$	8	3	4	1	1
$72 \leqslant \theta < 80$	1	0	0	0	0

4. Analysis of results

A difficulty exists in determining the absolute muon flux in this type of measurement owing to the possibility of the telescope responding to shower particles accompanying muons, which themselves miss the apparatus. This would have the effect of increasing the observed flux, unless a correction can be made for the out-of-geometry muons. As the proportion of multiple events increases with depth, while the absolute intensity of particles decreases, it is clear that, if the enhancement effect is at all significant, it will be most noticeable at the greatest depth.

4.1. *Comparison of floor and roof runs at* 2235 *hg cm*$^{-2}$

To investigate the effect of the possible detection of out-of-geometry muons, two separate runs were taken at a depth of 2235 hg cm^{-2}. In the first, the apparatus stood on the floor of the mine gallery and, in the second, it was suspended close to the roof approximately 3 m above.

If the telescope was responding to out-of-geometry muons as a consequence of detecting the secondary particles only, then it would be expected that the counting rate in the floor position would exceed that in the roof position. This is because the majority of the secondary particles will be detected close to the parent muon, even if the angle between them is large, when the apparatus is close to the roof. As the distance between the roof and the apparatus increases, the lateral spread of the particles produced at a given angle and subsequently detected will increase. Hence, with increasing distance between the points of production and detection, more particles should be sufficiently far from their parent muon to be detected even though the muons miss the apparatus. It will be seen from the counting rates in table 2 that there is little evidence for a change in counting rate with position. This suggests that the shower particles are closely collimated (relative to the dimensions of the apparatus).

This was further investigated by means of a detailed analysis of the Geiger counter hodoscope records for the multiple events observed in the two runs. The term 'multiplicity' is defined as the total number of Geiger counters discharged in both trays in an event, and the term 'separation' is defined as the difference between the maximum and minimum serial numbers for the counters discharged in a tray. Where the separation is different for the two trays, the greater separation is used.

The separation is shown plotted against multiplicity in figure 4. In the diagrams the lower line indicates the boundary of possible events, and points on this line represent the discharge of groups of adjacent counters. Points far from this line represent the discharge

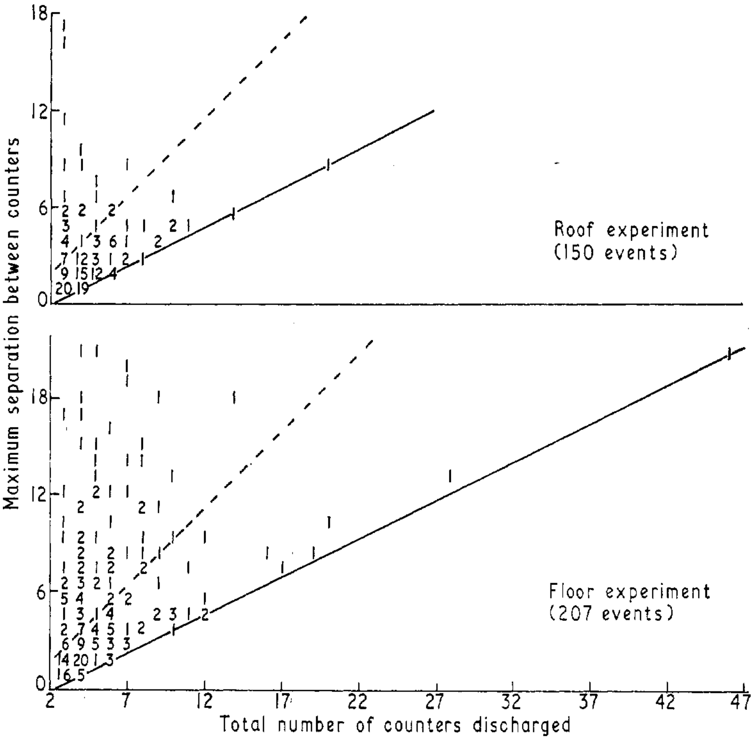

Figure 4. Multiplicity and separation at 2235 hg cm^{-2}.

of widely separated counters. The upper line, drawn at 45° to the axes, indicates the approximate boundary between events which consist of separated counters and those which consist of closely packed counters. In the roof run 86% of the events lie within the close-packed region compared with 66% in the floor run. The proportion of events for which the separation is less than or equal to six counters (equivalent to one-quarter of the length of the telescope) is 92% for the roof run and 68% for the floor run. From either of these two pairs of figures it is seen that about 20% of the multiple events have spread out considerably within the gallery. By considering the distribution of points of impact of incident particles and the spread of showers indicated by these figures, it has been estimated that the number of out-of-geometry particles recorded by the apparatus on the floor is about 10% of the number of multiples (the correction is negligible for the roof run). The overall correction to the intensity at 2235 hg cm^{-2} is only -1%, so that it does not appear necessary to make a more precise estimate. A similar correction was also applied at the other depths, based on the number of multiple events found.

4.2. *Angular distribution*

Following Barrett *et al.* (1952), it has been customary to assume that the angular distribution relating the intensity I_θ of muons observed at zenith angle θ to the vertical intensity I_{V} is given by

$$I_\theta = I_{\mathrm{V}} \cos^n \theta.$$

Menon *et al.* (1967) have now shown that this expression is inadequate at depths below 4000 hg cm^{-2} for angles greater than about 40°. At the depths considered in the present experiment the angular restriction is less severe and, as can be seen from figure 5, the expression is still sufficiently accurate for angles up to approximately 60°.

Corrections were applied to the results previously shown in table 3 to allow for the increasing separation of the telescope trays, the reduction in the detection area with increasing zenith angle and for the finite length of the Geiger counters. The exponent

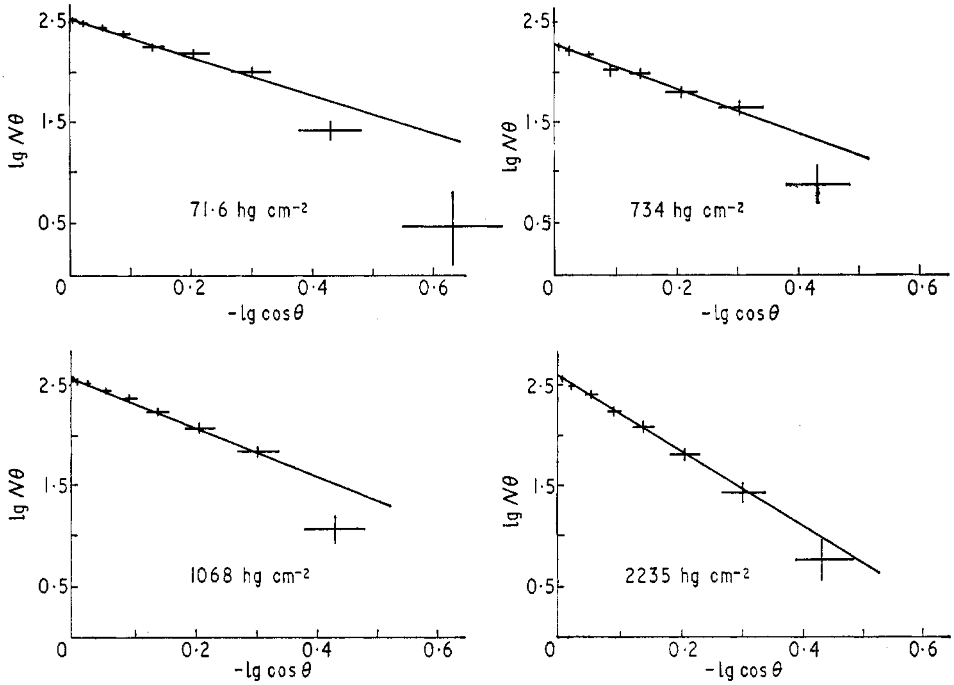

Figure 5. Angular distributions of muons at various depths underground.

n was obtained for each depth from the best-straight-line fit to the lg–lg graphs shown in figure 5, with a cut-off at 60°. As there was no significant difference in the distributions from the floor and roof runs at 2235 hg cm^{-2}, they were combined.

4.3. *Intensity*

In order to obtain the vertical intensity of muons from measurements of the counting rate, it is necessary to know the aperture of the cosmic-ray telescope. As the aperture is not constant but depends on n and hence varies with depth, it was calculated for integral values of n from 0 to 6 from an expression derived by Stern (1960), which is a completely general method for any vertical rectangular telescope. Values of aperture for the best-fit values of n were interpolated for each depth and used to calculate the vertical intensities shown in table 4. These values have been corrected for the effects of out-of-geometry muons and for losses in the Geiger counter walls. The intensity given for 2235 hg cm^{-2} is an average of the floor and roof values.

Table 4. Vertical intensity

Depth (hg cm^{-2})	Adopted value of n	Aperture (cm^2 sr)	Vertical intensity (s^{-1} cm^{-2} sr^{-1})
71·6	1·85 ± 0·10	4560 ± 80	(5·00 ± 0·17) × 10^{-4}
734	2·1 ± 0·1	4330 ± 80	(3·12 ± 0·15) × 10^{-6}
1068	2·4 ± 0·1	4080 ± 80	(1·03 ± 0·04) × 10^{-6}
2235	3·6 ± 0·2	3280 ± 90	(9·7 ± 0·5) × 10^{-8}

An examination of all previous underground intensity measurements has shown that there is a surprising lack of reliable data at comparatively shallow depths, although below about 1000 hg cm^{-2} our knowledge of the intensity–depth curve is relatively good. This situation is due to the fact that the majority of measurements at shallow depths have not been absolute measurements, but have been normalized to values predicted from sea-level momentum spectrograph measurements and the energy-loss equation. Several of the

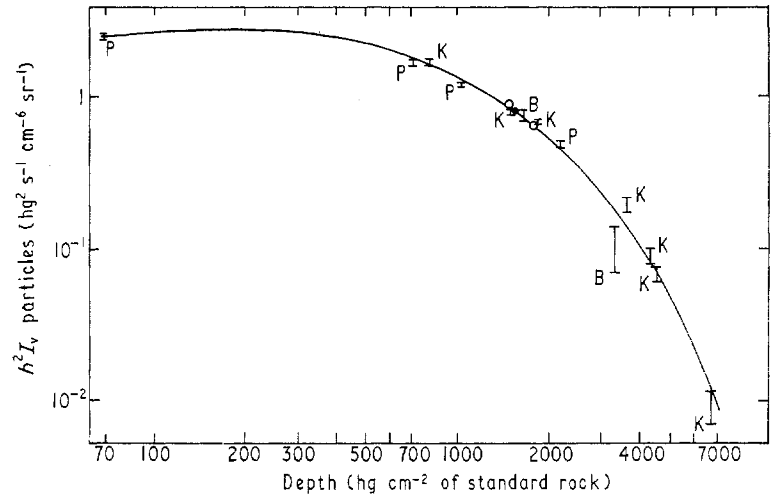

Figure 6. Intensity–depth curve: ○ Bollinger 1951; ● Barrett *et al.* 1952; B Barton 1961; K Kolar gold mine experiments, Miyake *et al.* 1964, Achar *et al.* 1965, Krishnaswamy *et al.* 1968; P present experiment; — empirical formula.

earlier intensity measurements were also made under water, for which the Z/A and Z^2/A values are sufficiently different from those of standard rock to require large corrections to make them comparable. Those of the previous absolute measurements, which are considered to be reasonably reliable, have been included with the present results in the new intensity–depth curve shown in figure 6. The ordinate of this curve is shown as the product of intensity times depth squared ($I_v h^2$) in order to display the results more clearly.

An empirical relationship of the form

$$I = A_0 \frac{h^{-\alpha}}{h+h_1} \mathrm{e}^{-\beta h} \text{ particles s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}$$

originally proposed by Miyake (1963), has been fitted to the curve and best agreement was obtained using values of $A_0 = 45$, $\alpha = 1{\cdot}38$, $h_1 = 162{\cdot}5$ and $\beta = 7{\cdot}05 \times 10^{-4}$, but it should be noted that other sets of values can also give a satisfactory fit.

4.4. *Discussion*

Following Barrett *et al.* (1952), the exponent of the intensity–depth curve is defined as

$$m = -\frac{\partial \lg I}{\partial \lg h} = -\frac{h}{I}\frac{\partial I}{\partial h}$$

and $\delta = m - n$, when measured at the same effective depth. For this purpose any values of n, measured at depth h, must be plotted at depth $h \sec \bar{\theta}$ in order to compare with the corresponding variation of m with depth, where $\bar{\theta}$ is the mean zenith angle of the muons observed. The need to correct the depth to which a measurement of n corresponds has not been appreciated by several authors subsequent to Barrett *et al.* The latter estimated that for their apparatus $\bar{\theta}$ was about 30°, and this value is a sufficiently good approximation in interpreting other data for which a more precise value is not available. The discrepancy of two standard deviations between theory and experiment for n in the region of 1500 hg cm^{-2} found by Achar *et al.* (1965) is removed when this correction is applied.

Theoretical values of δ have been deduced on the assumption that 80% of muons arise from pion decay and 20% from kaon decay, and used to derive the expected variation of n with depth. This is shown in figure 7, where satisfactory agreement with the expermental values is obtained. The curve is not critically dependent on the exact K/π ratio adopted (Achar *et al.* 1965).

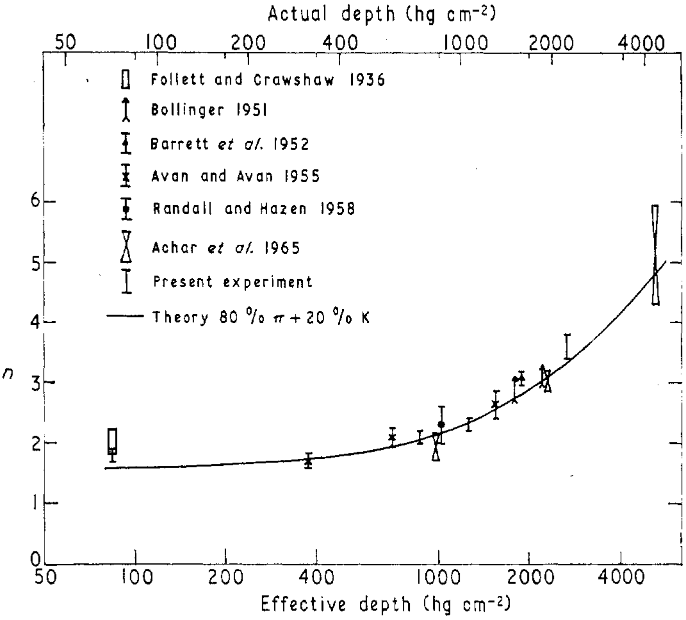

Figure 7. Comparison between observed and predicted values of n.

An alternative method of analysing the angular distribution data, suggested by Menon *et al.* (1967), avoids the use of the exponent n; this method will certainly be necessary at greater depths, but the original method of Barrett *et al.*, appears to be adequate at the more moderate depths for which accurate data are available. Bergeson *et al.* (1967) used the University of Utah neutrino detector, located at a depth of approximately 1500 hg cm^{-2} to measure the intensity of cosmic-ray muons as a function of depth and zenith angle. They found almost no variation of intensity with zenith angle, in contrast to the sec θ enhancement, which was assumed by Menon *et al.* (1967) and is implied if pions and kaons are the parents of the muons observed underground. In particular, if the intensity $I(h, \theta)$ at vertical depth h in direction θ is related to the vertical intensity $I(h \sec \theta, 0)$ at slant depth $h \sec \theta$ by

$$I(h, \theta) = I(h \sec \theta, 0) \sec^{s} \theta$$

Bergeson *et al.* found that $s = 0{\cdot}25 \pm 0{\cdot}09$ and concluded that the majority of the muons they observed did not result from pion and kaon decay, but were directly produced in the primary cosmic-ray interactions. Keuffel (1968) re-analysed the results of the Utah experiment, and suggested that part of the discrepancy may be due to underestimating the rock density by some 5%. This correction gives a revised value of $s \simeq 0{\cdot}5$ at 2000 hg cm^{-2}.

This alternative method of analysis has also been applied to the results of the present experiment. The corrected angular distributions for the depths of 1068 hg cm^{-2} and 2235 hg cm^{-2} have been taken, together with intensities from figure 6, to find the best-fit values of s using the chi-square test: $s = 0{\cdot}75 \pm 0{\cdot}20$ at 1068 hg cm^{-2} and $s = 0{\cdot}85 \pm 0{\cdot}25$ at 2235 hg cm^{-2}. The ratio of observed to predicted intensities at 2235 hg cm^{-2}, on the assumption that $I(h, \theta) = I(h \sec \theta, 0) \sec^{0{\cdot}85}\theta$, is plotted against slant depth $h \sec \theta$ in figure 8. These results are clearly in disagreement with that of Bergeson *et al.*, but are not completely incompatible with the revised value of Keuffel in view of the relatively poor statistical accuracy.

However, it can be shown that s is the same as δ and consequently its theoretical variation with depth is known. For a K/π ratio of 20% Achar *et al.* predict $\delta = 0{\cdot}8$ at 2000 hg cm^{-2}, which is in good agreement with the results of the present experiment but disagrees with the Utah results. The value of δ is not particularly sensitive to the exact K/π ratio adopted. It should be noted that a full sec θ enhancement is not predicted theoretically until a depth of the order of 5000 hg cm^{-2} is reached. One cannot, of course, exclude the possibility that a small proportion of muons are produced by a direct production process, but there seems little or no justification for introducing any such new physical process. The same conclusion has been reached in a recent measurement of the angular distribution underground by Krishnaswamy *et al.* (1968). It is likely that the remaining discrepancy between the Utah results and other measurements may be due to uncertainties in the effective depth and in the assumed intensity–depth curve, as the method of analysis of Bergeson *et al.* and Keuffel is rather sensitive to the assumed vertical intensity, which cannot be measured with the same apparatus, and, as can be seen in figure 6, is only known to within about ±10%.

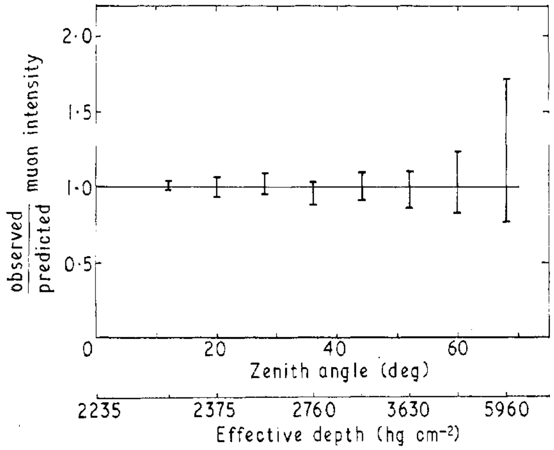

Figure 8. Comparison between observed and predicted muon intensity, on the assumption that $I(h, \theta) = I(h \sec \theta, 0) \sec^{0.85} \theta$.

5. Conclusions

A comparison of the results of the present experiment with those from previous experiments shows good agreement for the variation of both n and vertical intensity with depth. The n–depth curve (figure 7) is considered to have an uncertainty of approximately ±10% in the region from 70 to 2235 hg cm^{-2}, increasing to approximately ±15% at 4370 hg cm^{-2}, below which no data are available, and in any case it will be necessary to analyse the data in a different manner. The intensity–depth curve (figure 6) is uncertain to the extent of approximately ±10% in the region from 70 to 5000 hg cm^{-2} and then increasing to approximately ±20% down to 7000 hg cm^{-2}. At greater depths muon vertical intensities have only been deduced by Menon *et al.*, (1967) from experiments designed to detect neutrinos, and these have uncertainties of the order of ±30%.

In order to improve the accuracy of the n–depth and intensity–depth curves, it is desirable to concentrate on the measurement of the angular distribution of muons at a series of accurately known depths. This is because it is always possible to derive the vertical intensity from a measurement of the angular distribution, while the converse is not necessarily true. While the accuracy of intensity determinations is largely set by the duration of the experiment, which at least in principle may be chosen to give any desired value, the ultimate value of such underground experiments depends largely on the precision of the measurements of depth. Owing to the shape of the intensity–depth curve, a small change in depth is equivalent to a significant change in intensity. Although the precision of depth measurements is seldom quoted in publications, they are likely to be uncertain to the extent of at least ±2%. The greater accuracy obtained in the present experiment is due to exceptionally favourable circumstances in that the rock density is well known from gravity surveys and the surrounding terrain is relatively flat.

Although the present apparatus has given satisfactory results, it is not the most suitable that can be devised. Its design was restricted for reasons of portability and operating convenience, and a larger apparatus, with a more accurate hodoscope, would be desirable. The present apparatus is, however, the first in which full use has been made of the energy-measuring properties of a scintillation counter, and a discussion of the significance of the observed energy losses for muons is presented in the following paper (Barton and Stockel 1969).

Acknowledgments

The author wishes to thank the London Transport Board and the National Coal Board for permission to work in the Holborn Underground Laboratory and at Tilmanstone Colliery respectively.

It is a pleasure to acknowledge the assistance freely given by the following staff of the National Coal Board: Mr. D. A. Tanfield (Research and Development Department, London), Mr. F. Henley Price (Chief Scientist, Kent), Mr. F. S. Garrett (Analyst, Central Laboratories, Eythorne), Mr. C. Harris (Laboratory Manager, Eythorne), Mr. W. Marsh (Foreman Shaftsman, Tilmanstone Colliery), and others too numerous to mention, without whose enthusiastic co-operation this experiment could not have been performed.

The author is indebted to Mr. R. Wynne (National College of Rubber Technology), who designed and supplied the rubber blocks used in the telescope mounting, and to Mr. W. F. Carter, Mr. G. W. Dickson and Mr. V. G. Wordley for their assistance in the construction of the apparatus.

References

Achar, C. V., *et al.*, 1965, *Proc. Phys. Soc.*, **86**, 1305–15.
Avan, M., and Avan, L., 1955, *C.R. Acad. Sci., Paris*, **241**, 1122.
Barrett, P. H., *et al.*, 1952, *Rev. Mod. Phys.*, **24**, 133–78.
Barton, J. C., 1961, *Phil. Mag.*, **6**, 1271–83.
Barton, J. C., and Crispin, A., 1962, *Nucl. Instrum. Meth.*, **16**, 39–43.
Barton, J. C., and Stockel, C. T., 1964, *Radio Electron. Engng*, **27**, 11–8.
—— 1969, *J. Phys.* A (*Gen. Phys.*), [2], **2**, 650–7.
Bergeson, H. E., *et al.*, 1967, *Phys. Rev. Lett.*, **19**, 1487–91.
Bollinger, L. M., 1951, *Ph.D. Thesis*, Cornell University.
Bullerwell, W., 1954, *Bull. Geol. Soc. G.B.*, **6**, 13–20.
Domzalski, W., 1954, *Trans. Inst. Mining and Metallurgy*, **63**, 429–45.
Follett, D. H., and Crawshaw, J. D., 1936, *Proc. R. Soc.* A, **155**, 546–58.
George, E. P., 1952, *Progress in Cosmic Ray Physics*, **1**, 395–451 (Amsterdam: North-Holland).
Hunter, H. W., 1961, *Ph.D. Thesis*, University of London.
Keuffel, J. W., 1968, *Proc. Utah Acad. Sci.*, **45**, 1–16.
Krishnaswamy, M. R., *et al.*, 1968, *Phys. Lett.*, **27B**, 535–8.
Mando, M., and Ronchi, L., 1952, *Nuovo Cim.*, **9**, 517–28.
Menon, M. G. K., and Ramana Murthy, P. V., 1967, *Progress in Elementary Particle and Cosmic Ray Physics*, **9**, 161–243 (Amsterdam: North-Holland).
Menon, M. G. K., *et al.*, 1967, *Proc. Phys. Soc.*, **90**, 649–56.
Miyake, S., 1963, *J. Phys. Soc. Japan.*, **18**, 1093.
Miyake, S., Narasimham, V. S., and Ramana Murthy, P. V., 1964, *Nuovo Cim.*, **32**, 1505–23.
Randall, C. A., and Hazen, E., 1958, *Nuovo Cim.*, **8**, 878–81.
Stern, D., 1960, *Nuovo Cim.* (*Suppl.*), **16**, 153–7.