

# ON THE ANGULAR DISTRIBUTION OF PENETRATING COSMIC-RAY PARTICLES AT A DEPTH 103 MWE BELOW GROUND

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Received January 16, 1956

(Communicated by Prof. B. Peters, F.A.Sc.)

## INTRODUCTION

THE measurement of the vertical intensity of cosmic radiation has been carried out by different workers<sup>1(a)-(e)</sup> upto a maximum depth of about 3,000 metres water equivalent (mwe). Barrett *et al.*<sup>2</sup> have combined the various measurements and after suitable normalisation, have found it possible to draw a smooth curve passing through all the experimental points.

Recently, we have made measurements of vertical intensities at depths 100, 381, 475, 684 and 885 mwe<sup>3\*</sup> in the Kolar Gold Mines (Mysore State). Our points also fall very close to the composite intensity-depth curve of Barrett *et al.* (Fig. 1). The slope of this composite curve is found to increase continuously with depth. It does not exhibit any abrupt changes in the slope, as was believed to be the case, a few years ago.

Absorption measurements of Barrett *et al.* at a depth of 1,574 mwe, have clearly shown that the penetrating particles observed underground, are not locally produced in the rock above the recording apparatus, but are produced high up in the atmosphere, and traverse all the way through the rock before reaching various depths. Cloud chamber experiments, carried out below ground, have revealed that the general features of the penetrating particles below ground are very similar to those exhibited by the penetrating particles at sea-level. This, together with the fact that the least interacting particle known so far, is the  $\mu$ -meson, makes it quite certain that the underground penetrating particles are essentially the high energy  $\mu$ -mesons encountered at sea-level.

Therefore, the behaviour of the intensity-depth curve depends upon

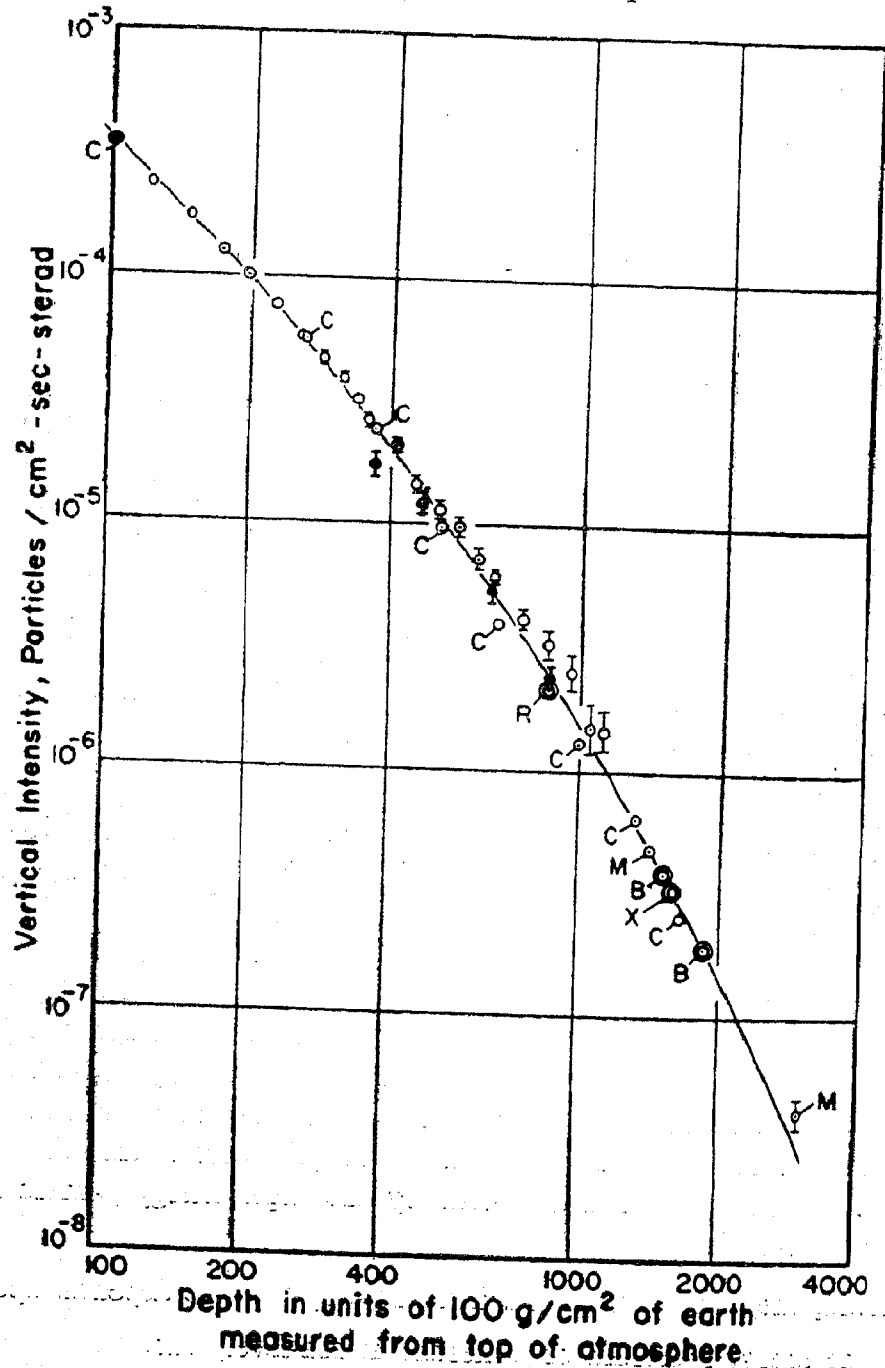
(a) the energy spectrum of  $\mu$ -mesons at sea-level, and

(b) the range-energy relation of  $\mu$ -mesons.

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\* The depths quoted in (3) were in error and have been corrected in this paper.

It is well known that  $\mu$ -mesons are not produced directly in nuclear interactions. They are the decay products of heavier mesons. Therefore, the sea-level spectrum of  $\mu$ -mesons depends upon



○ V.C.Wilson, C=Clay and Gemert, B=Bollinger, R=Randall and Hazen, M=Miyazaki, X=Barret Etal.

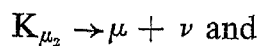
● Present Experiment.

FIG. 1

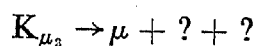
- (i) the production spectrum of the parents of  $\mu$ -mesons, and
- (ii) the mass, mean life-time, absorption mean free path, and relative abundance of the parent particles.

At present two definite sources of  $\mu$ -mesons have been established, *viz.*, the  $\pi$ -mesons and some of the K-mesons. The mass, life-time and absorption mean free path of  $\pi$ -mesons are very well established. The properties of K-mesons are however not so well determined yet. Among the K-mesons, which decay into  $\mu$ -mesons, two types have been recognised.

- (a) the  $K_{\mu_2}$ , which undergoes decay according to the two-body decay scheme



- (b) the  $K_{\mu_3}$ , or the kappa-meson which decays according to the three-body decay scheme



Evidence for  $K_{\mu_2}$ , undergoing a two-body decay, was first obtained by the Ecole Polytechnique group.<sup>4</sup> Bridge *et al.*<sup>5a</sup> measured the range of  $\mu$ -mesons emitted by  $K_{\mu_2}$  mesons stopped in a multi-plate cloud chamber, and deduced the mass of  $K_{\mu_2}$  as  $950 \pm 15 m_e$ . From direct measurements on  $K_{\mu_2}$  particle, as well as measurement of the range of the secondary  $\mu$ -meson, Armenteros *et al.*<sup>5b</sup> obtained  $935 \pm 15 m_e$  as the best mass value of  $K_{\mu_2}$ . Direct timing measurements on the life-times of K-particles by Robinson,<sup>6</sup> and Barker *et al.*<sup>7</sup> indicate that the  $K_{\mu_2}$  life-time is of the order of  $10^{-8}$  secs.

Evidence for  $K_{\mu_3}$  or kappa mesons was first found by Menon and O'Ceallaigh<sup>8</sup> in photographic emulsions. Direct evidence for the three-body decay scheme involving a  $\mu$ -meson is obtained from four cases (Bristol, Rome, Rochester and Paris), in which the secondary energies suggested a continuous energy distribution. The secondaries were identified as  $\mu$ -mesons by  $\mu$ -e decay. The best estimate of the mass of  $K_{\mu_3}$  is  $1035 \pm 25 m_e$ .<sup>9</sup> Armenteros *et al.*<sup>10</sup> give a life-time of the order of  $10^{-9}$  secs. for  $K_{\mu_3}$  particles. The relative abundance of  $K_{\mu_2}$  and  $K_{\mu_3}$  is not well known. An absolute upper limit to the ratio of charged heavy mesons to charged  $\pi$ -mesons, produced at very high energies, is deduced to be 25%.<sup>11</sup>

At low energies all the  $\pi$  and  $K_{\mu}$ -mesons decay into  $\mu$ -mesons. But as the energy increases, due to relativistic increase of the life-time competition between absorption and decay sets in. This results in a progressive deficiency in the number of  $\mu$ -mesons at the high energy end. Using the decay

and absorption constants, it is possible to work out theoretically, the sea-level  $\mu$ -meson spectrum provided the production spectrum of the parent particles is known.

In Section I of this paper, we have presented arguments to show that a measurement of zenithal angular distribution of penetrating particles at a depth of about 100 mwe, will enable us to accurately determine the production spectrum of the parents of  $\mu$ -mesons. We have also shown that this determination is fairly independent of the nature and composition of the parent particles.

In Section II, we have given the results of an experiment on the angular distribution of penetrating particles, carried out at a depth of 103 mwe, with a hodoscoped counter telescope. The experimental results indicate a power law production for the parents of the  $\mu$ -mesons with an exponent  $-1.92 \pm 0.08$ .

In Section III, we have calculated the theoretical intensity-depth curves for different conditions of production of the parents of  $\mu$ -mesons and also using different range-energy relations of  $\mu$ -mesons. The theoretical curves have been compared with the experimental intensity depth curve. The conclusions that can be drawn from the comparison are discussed.

#### SECTION I. RELATION BETWEEN THE ANGULAR DISTRIBUTION OF UNDERGROUND $\mu$ -MESONS AND THE PRODUCTION SPECTRUM OF PARENTS OF $\mu$ -MESONS

Let us consider, for the present, the production of  $\pi$ -mesons alone in the nuclear interactions of the primaries. The  $\pi$ -mesons are known to decay with a life-time  $2.56 \times 10^{-8}$  secs. into  $\mu$ -mesons. There is now substantial evidence to show that the  $\pi$ -mesons<sup>12</sup> and primary protons which produce them interact with nuclear geometric cross-section upto energies of the order of  $10^{11}$  ev. Considering the competition between decay and absorption of  $\pi$ -mesons, it is easy to derive (see Barrett *et al.*) the following expression for the sea-level intensity of  $\mu$ -mesons arriving at an angle  $\theta$  with respect to the vertical, with an energy greater than  $E_\theta$  at production:

$$I(E_\theta, \theta) = K_\pi \cdot \left(\frac{\gamma_\pi}{E_\theta}\right)^\epsilon \frac{B_\pi}{(\epsilon + 1) E_\theta \cos \theta + \epsilon B_\pi + \frac{\sqrt{B_\pi E_\theta \cos \theta}}{2\epsilon + 1}} \quad (1)$$

where  $E_\theta$  = minimum energy of the  $\mu$ -mesons at the production layer.

$\epsilon$  = the exponent in the integral spectrum of  $\pi$ -mesons at production, assumed to follow a power law.

$$B_{\pi} = \frac{m_{\pi} c^2 \cdot \gamma_{\pi} \cdot H}{c\tau_{\pi}}$$

$m_{\pi} c^2$  = rest energy of  $\pi$ -mesons = 0.140 Bev.

$\gamma_{\pi}$  = energy degradation factor in  $\pi$ - $\mu$  decay = 0.76.

$\tau_{\pi}$  = mean life-time of  $\pi$ -mesons =  $2.56 \times 10^{-8}$  secs.

H = equivalent atmospheric depth in cm. =  $6.46 \times 10^5$  cm.

$K_{\pi}$  = a constant.

Upto fairly high energies, about 100 Bev, it is reasonable to assume the range-energy relation of relativistic  $\mu$ -mesons to be linear, so that

$$E = \alpha \cdot R \quad (2)$$

where R is the range of  $\mu$ -mesons in mwe, and  $\alpha$  is a constant giving the rate of loss of energy per mwe.

The minimum energy  $E_{\theta}$  that a  $\mu$ -meson should have at the top of the atmosphere, in order to arrive at a depth D, at an angle  $\theta$  with respect to the vertical,

$$E_{\theta} = \alpha R_{\theta} \quad (3)$$

where  $R_{\theta}$  is the amount of matter encountered by the  $\mu$ -meson in the direction  $\theta$  and is given by

$$R_{\theta} = D/\cos \theta. \quad (4)$$

From (3) and (4),

$$E_{\theta} = \alpha D/\cos \theta. \quad (5)$$

Substituting the expression for  $E_{\theta}$  given by (5) in (1), we obtain the expression for the intensity of  $\mu$ -mesons arriving at an angle  $\theta$  with respect to the vertical, at a depth D mwe below the top of the atmosphere,

$$I_D(\theta) = K_{\pi} \cdot \left( \frac{\gamma_{\pi} \cos \theta}{\alpha D} \right)^{\epsilon} \frac{B_{\pi}}{(\epsilon + 1) \alpha D + \epsilon B_{\pi} + \frac{\sqrt{B_{\pi} \alpha D}}{2\epsilon + 1}} \quad (6)$$

$$= \text{constant} \cdot \cos^{\epsilon} \theta \quad (7)$$

since  $\gamma_{\pi}$ ,  $\tau_{\pi}$ , D,  $B_{\pi}$  and  $\epsilon$  are all constants. Therefore, the exponent in the cosine law for the angular distribution of underground  $\mu$ -mesons gives the exponent in the generation spectrum of  $\pi$ -mesons.

Let us now take into consideration the production of  $K_{\mu}$ -mesons as well. If the production spectrum of  $K_{\mu}$ 's and  $\pi$ 's follow the same power law, then from an exactly similar treatment as above, we have

$$\begin{aligned}
I_D(\theta) &= K_\pi \left( \frac{\gamma_\pi \cos \theta}{\alpha D} \right)^\epsilon \frac{B_\pi}{(\epsilon + 1) \alpha D + \epsilon B_\pi + \frac{\sqrt{B_\pi \alpha D}}{2\epsilon + 1}} \\
&+ K_k \left( \frac{\gamma_k \cos \theta}{\alpha D} \right)^\epsilon \frac{B_k}{(\epsilon + 1) \alpha D + \epsilon B_k + \frac{\sqrt{B_k \alpha D}}{2\epsilon + 1}} \\
&= \text{constant. } \cos^\epsilon \theta.
\end{aligned}$$

where  $K_k$ ,  $B_k$ ,  $m_k$ ,  $\gamma_k$  and  $\tau_k$  are constants referring to  $K_\mu$ -mesons.

Therefore, *provided the production spectrum of  $K_\mu$ -mesons and  $\pi$ -mesons is the same*, the angular distribution experiment gives the exponent in the production spectrum.

In the above analysis, we have assumed the range-energy relation of  $\mu$ -mesons to be linear. So it is essential that the angular distribution experiment is carried out at a depth for which this is true. The range-energy relation given by George<sup>13</sup> taking into consideration the energy losses due to ionisation, bremsstrahlung, pair production, nuclear interactions, and emission of Cerenkov radiation, is non-linear and can be expressed as follows:

$$R' = 1/b \ln(1 + bE/d) \quad (8)$$

where  $R'$  is the range of  $\mu$ -mesons expressed in gm. cm.<sup>-2</sup> and  $E$  is the energy of the  $\mu$ -mesons expressed in Mev.  $b = 5.26 \times 10^{-6}$  for rock of mean atomic number 10.5 and mean atomic weight 21.  $d = 2.65$  Mev. gm.<sup>-1</sup> cm.<sup>-2</sup>

In order to see to what extent the non-linearity of the equation (8) affects the validity of equation (7), at a depth of 100 mwe, values of  $E$  for  $\theta$  varying from  $0^\circ$  to  $75^\circ$  were calculated from (8) and substituted in (7). It was found that the value of the constant in equation (7) varied only by 4% in going from the vertical direction to an angle of  $75^\circ$ .

Therefore the measurements of the angular distribution of penetrating particles should give a fairly accurate determination of the production spectrum. Another advantage of working at a depth of 100 mwe is that the effect of the  $\mu$ - $e$  decay in the atmospheres of these energies is negligible.

In the following section we have described an experiment on the angular distribution of penetrating particles, carried out at a depth of 103 mwe.

## SECTION II. ANGULAR DISTRIBUTION OF PENETRATING PARTICLES AT A DEPTH OF 103 MWE

The experiment on the angular distribution of penetrating particles was carried out at a depth of 103 mwe, in the Gold Mines at Kolar, where the vertical intensity of cosmic rays was previously measured upto a depth

of 885 mwe. The counter geometry employed for the experiment is shown in Fig. 2. The counters were used in each of the trays A, B, C and D. Ten centimetres of lead were placed between the trays B and C. The separation between the extreme trays was 42 cm. The counter telescope was mounted in a steel frame which could be tilted about a horizontal axis and set at any desired inclination with respect to the vertical.

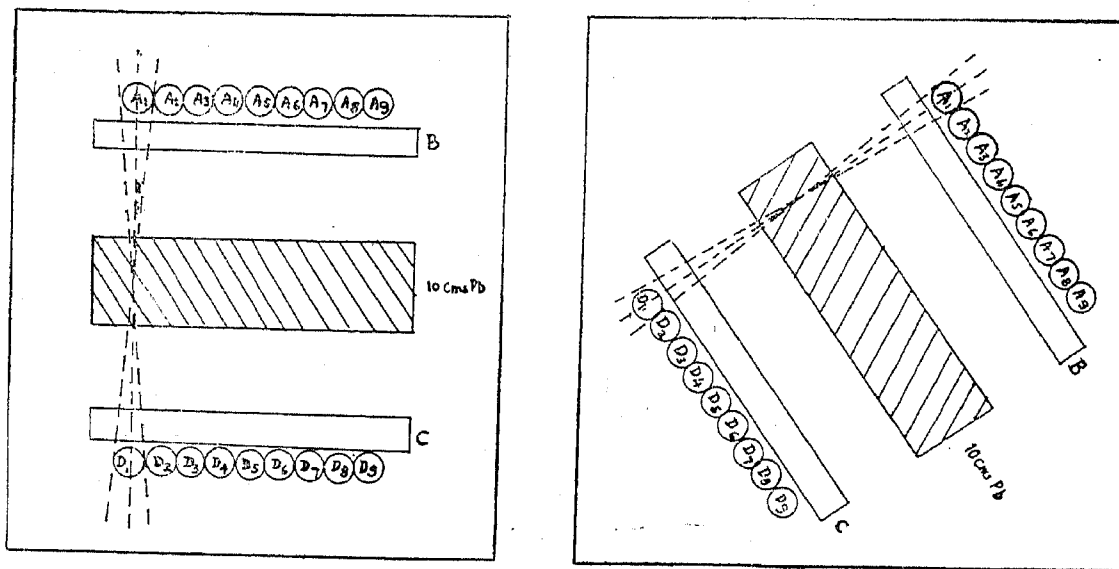


FIG. 2. Counter telescope used for the angular distribution experiment.

With a hodoscope arrangement, similar to the one described in a previous paper (reference 3), the following counting rates were recorded for inclinations of  $0^\circ$ ,  $45^\circ$ ,  $60^\circ$ ,  $65^\circ$ ,  $75^\circ$  and  $90^\circ$  with respect to the vertical.

(a) two-fold coincidence rates  $A_i D_i$  of the nine parallel single counter telescopes formed by corresponding pair of counters in trays A and D ( $i = 1 \dots 9$ )

(b) three-fold coincidence rates  $A_i B D_i$  ( $i = 1 \dots 9$ )

(c) three-fold coincidence rates  $A_i C D_i$  ( $i = 1 \dots 9$ )

and (d) four-fold coincidence rates  $A_i B C D_i$  ( $i = 1 \dots 9$ )

In Table I we have given the coincidence rates (d) and the sum of the coincidence rates (b), (c) and (d) in all the nine channels, for different inclinations of the telescope. These counting rates are corrected for showers as described below.

#### Shower Correction

As is the usual practice in all angular distribution measurements, the shower correction has been obtained by recording the counting rate with

TABLE I. Angular Distribution of Penetrating Particles at 103 Metres Water Equivalent

Angle	Time in Hours	Total number of triple coincidences, (b) + (c) + (d)			Total number of four-fold coincidences, (d)		
		Number of counts	Rate (counts/hour)	Rate (counts/hour) corrected for showers	Number of counts	Rate (counts/hour)	Rate (counts/hour) corrected for showers
0°	18.00	1,671	92.83 ± 2.27	84.8 ± 2.3	1,090	60.56 ± 1.83	56.4 ± 1.85
45°	19.42	1,002	51.6 ± 1.6	43.6 ± 1.64	684	35.26 ± 1.35	31.1 ± 1.37
60°	23.00	662	28.8 ± 1.1	20.8 ± 1.0	413	17.96 ± 0.88	13.8 ± 0.90
65°	41.00	995	24.3 ± 0.8	16.3 ± 0.90	642	15.66 ± 0.62	11.5 ± 0.67
75°	89.00	1,232	13.84 ± 0.4	5.84 ± 0.50	778	8.74 ± 0.30	4.6 ± 0.40
90°	69.00	552	8.00 ± 0.34	..	285	4.15 ± 0.24	..



the telescope tilted horizontal. For large angles, for which the shower correction is appreciable, the maximum contribution to the showers will be from the vertical direction. So far as these vertical showers are concerned, the disposition of the counters will remain practically the same for all angles greater than  $45^\circ$ . Therefore, the horizontal counting rate should give a fairly accurate shower correction, for all large angles. To verify experimentally whether the horizontal reading gives a fairly reliable shower correction, measurements were made at sea-level, where the effect of side showers on telescope counting rates is not as significant as underground. With the same telescope at sea-level, the ratio of four-fold to three-fold coincidences before, and after shower correction, were almost equal (0.71), whereas below ground, the two ratios were significantly different (0.65 and 0.70 respectively), thereby showing that the contribution of side showers underground is more than at sea-level. The ratio of the number of particles causing four-fold and three-fold coincidences is a geometrical factor, arising purely out of leakage spaces in counter trays B and C. This factor should be the same at sea-level and underground. The ratio of four-fold to three-fold coincidences obtained *after subtracting the horizontal reading*, is found to agree with the geometrical factor at sea-level. This comparison indicates that the shower correction applied here is quite reliable.

The counting rates at different inclinations, corrected for showers by subtracting the horizontal counting rate from the observed counting rates, are given in columns 5 and 8. The sum of the counting rates (*b*), (*c*) and (*d*) corrected for showers is plotted against  $\cos \theta$  on a log-log scale in Fig. 3. It is seen that a straight line can be fitted to the experimental points. The slope of the line fitted by the method of least squares comes out to be  $1.92 \pm 0.08$ . Therefore, the angular distribution at a depth of 103 mwe can be expressed by the cosine law,

$$I(\theta) = I(0) \cos^{1.92 \pm 0.08} \theta$$

or *the exponent in the production spectrum of the parents of  $\mu$ -mesons is  $-1.92 \pm 0.08$ .*

### SECTION III. COMPARISON BETWEEN THE THEORETICAL AND EXPERIMENTAL INTENSITY-DEPTH CURVES

Using equation (1) in Section I, and the production spectrum  $E^{-1.92}$ , we have worked out the theoretical intensity-depth curves, considering the production of  $\pi$ -mesons alone in nuclear interactions of primaries, and assuming

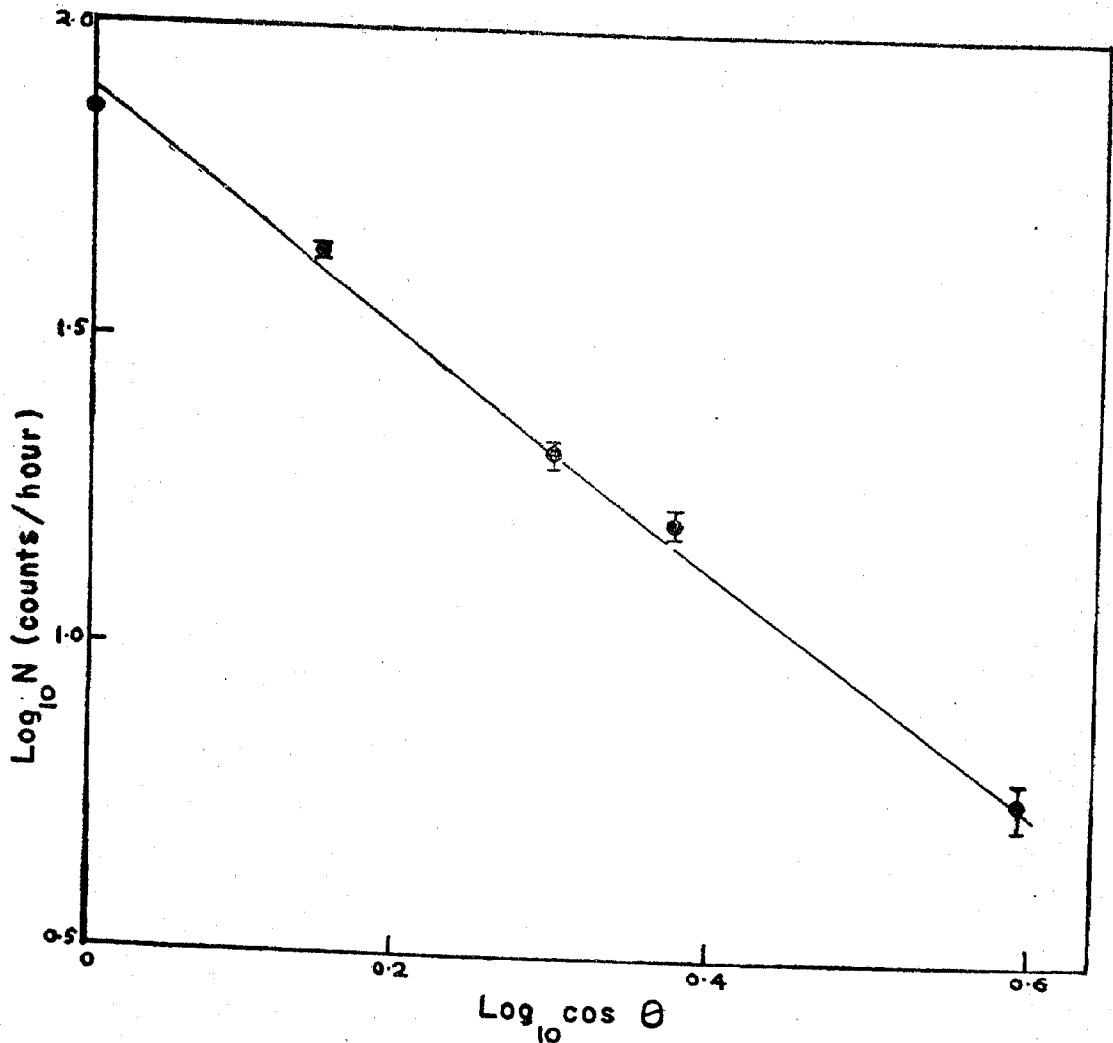


FIG. 3. Angular distribution of penetrating particles at 103 mwe.

- (a) the range-energy relation of  $\mu$ -mesons to be linear upto 300 Bev, and a constant energy loss of  $2.2 \text{ Mev gm.}^{-1} \text{ cm.}^2$
- (b) the range-energy relation given by George (equation 8 in Section II), which takes into account the various processes by which  $\mu$ -mesons lose energy.

These theoretical intensity-depth curves are compared with the experimental intensity-depth curve in Figs. 4 and 5, after normalising the theoretical intensity with the experimental value at a depth of 100 mwe. It is seen that while the theoretical curve drawn with the linear range-energy relation agrees reasonably well with the observed curve, the one drawn using the range-energy relation of George, deviates considerably from the experimental curve. The discrepancy is not removed to a great extent even if we take into

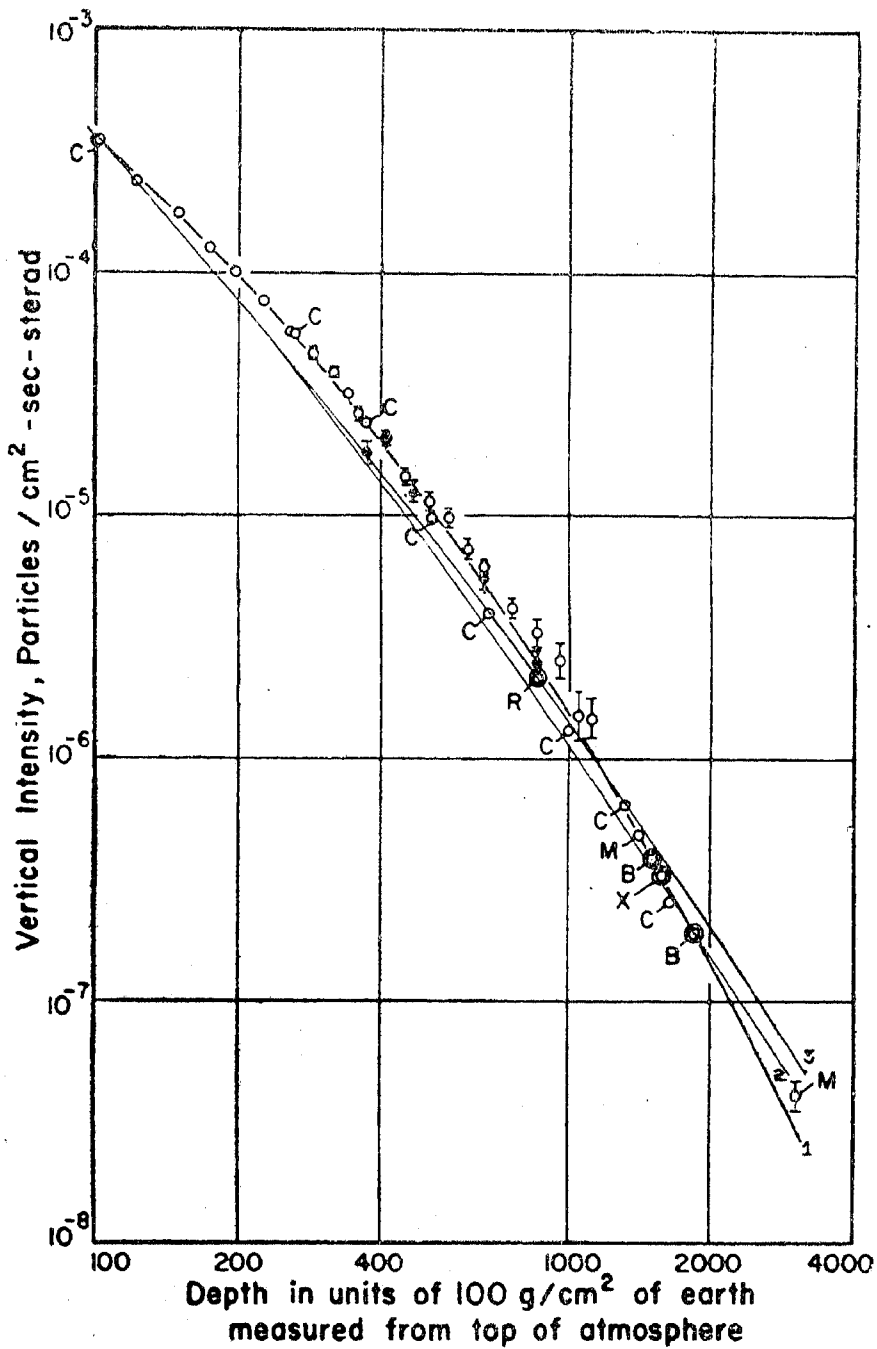


FIG. 4. Comparison between theoretical and experimental intensity-depth curves.

(1) Experimental intensity-depth curve.

*Theoretical intensity-depth curves*

with  $\epsilon = 1.92$ . Linear range-energy relation (energy loss =  $2.2 \text{ Mev. gm.}^{-1} \text{ cm.}^2$ ) and assuming

(2) Only  $\pi$ 's are the parents of  $\mu$ -mesons.

(3) Parents of  $\mu$ 's are  $\pi$ 's and  $K\mu$ 's in proportion 3 : 1,  $m_{K\mu} = 976 m_e$ ,  $\tau_{K\mu} = 10^{-8} \text{ secs}$ .

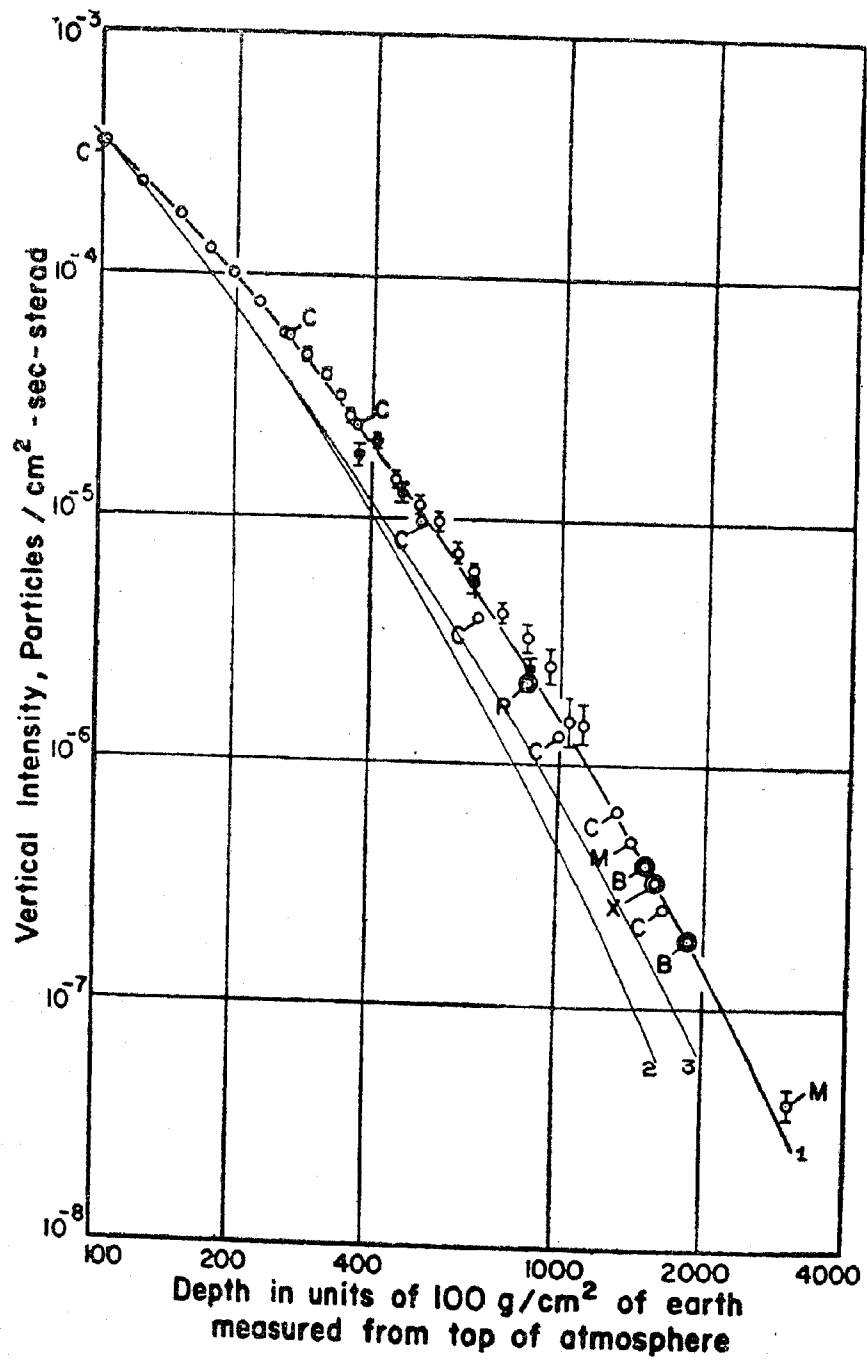


FIG. 5. Comparison between theoretical and experimental intensity-depth curves.

(1) Experimental intensity-depth curve.

*Theoretical intensity-depth curves*

with  $\epsilon = 1.92$  and assuming only  $\pi$ 's are parents of  $\mu$ -mesons, and George's range-energy relation (eq. 8).

(2) Including nuclear losses ( $b = 5.26 \times 10^{-6}$  in eq. 8).

(3) Excluding nuclear losses ( $b = 2.80 \times 10^{-6}$  in eq. 8).

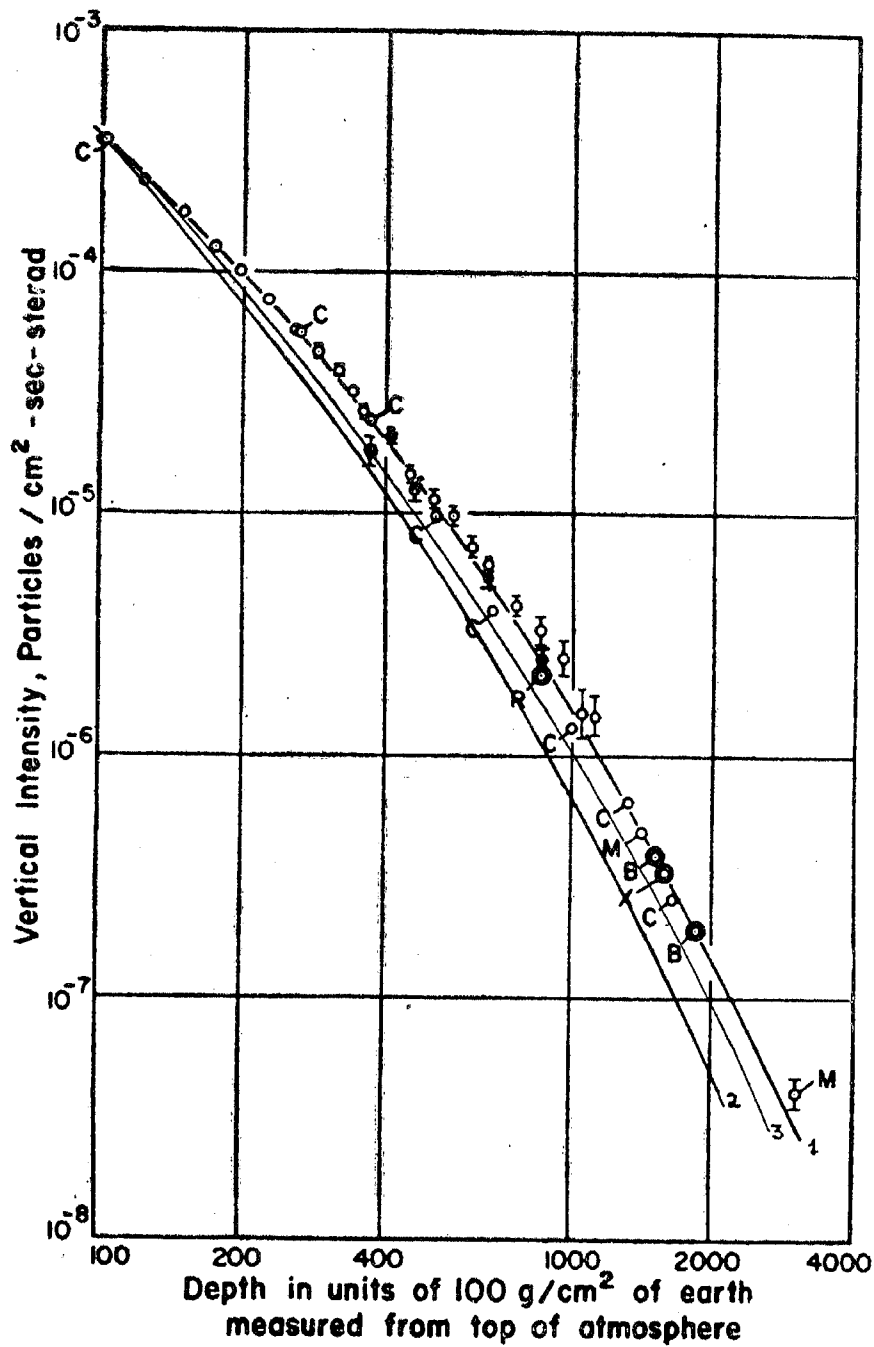


FIG. 6. Comparison between theoretical and experimental intensity-depth curves.

(1) Experimental intensity-depth curve.

*Theoretical intensity-depth curves*

with  $e = 1.92$  and assuming George's range-energy relation (eq. 8) and  $\pi$ 's and  $K\mu$ 's are parents of  $\mu$ 's in proportion.

(2)  $\pi : K\mu = 3 : 1$  ( $\tau_{K\mu} = 10^{-8}$  secs.).

(3)  $\pi : K\mu = 1 : 1$  ( $\tau_{K\mu} = 10^{-9}$  secs.).

consideration only the ionisation and electromagnetic energy losses of  $\mu$ -mesons, and ignore completely energy loss due to nuclear interactions, as shown in Fig. 5 (curve 3). In order to see whether the production, in addition to  $\pi$ 's of mesons other than  $\pi$ 's which have a life-time less than that of  $\pi$ 's, as for example the  $K_\mu$ 's, will remove the discrepancy between the observed and theoretical intensity-depth curves, we have calculated the theoretical intensity-depth curves for the following composition of the parents of  $\mu$ -mesons:

- (i)  $\pi$ -mesons:  $K_\mu$ -mesons = 3:1       $\tau_{K_\mu} = 10^{-8}$  secs.  
 (ii)  $\pi$ -mesons:  $K_\mu$ -mesons = 1:1       $\tau_{K_\mu} = 10^{-9}$  secs.

assuming  $r_k$ , the mean fraction of energy of  $K_\mu$  transferred to  $\mu$ -meson as 0.5.

It is seen from Fig. 6, curve 2 that even a high percentage of  $K_\mu$  production assumed in (i) is inadequate to explain the intensity-depth curve. Curve 3 in Fig. 6 indicates that unless  $K_\mu$ -mesons are produced in at least as large number as  $\pi$ 's and have a life-time less than  $10^{-9}$  secs., the observed intensity-depth curve cannot be explained, if we take the integral production spectrum  $E^{-1.92}$  and take into consideration all the energy losses of  $\mu$ -mesons in the formulation of the range-energy relation of  $\mu$ -mesons.

#### DISCUSSION

If we consider the production of  $\pi$ -mesons alone in the nuclear interactions of the primaries, then in order to remove the discrepancy between the observed and theoretical intensity-depth curves, either

- (a) the range-energy relation of  $\mu$ -mesons has to be linear upto 300 Bev. (energy loss not greater than  $2.2 \text{ Mev gm.}^{-1} \text{ cm.}^2$ ).  
 or (b) the production spectrum of  $\pi$ -mesons should be a power law with an exponent very much lower than 1.8 (about 1.5).

There is sufficient experimental evidence to indicate that the energy loss of  $\mu$ -mesons due to electromagnetic processes like radiation and pair production, does increase with increasing energy of  $\mu$ -mesons. The increase of the soft component in equilibrium with the penetrating component is a clear indication of increased energy losses. Therefore there seems to be no reason for questioning the validity of the range-energy relation of  $\mu$ -mesons given by George.

On the other hand, none of the angular distribution measurements carried out so far has given an exponent lower than 1.8 for the production spectrum. Follet and Crawshaw<sup>14</sup> working at a depth of 60 mwe, obtained for the power of the cosine law the value  $2.02 \pm 0.2$ . Quercia and Rispoli<sup>1</sup>

have made a measurement of the angular distribution of penetrating particles at a depth of 40 metres in water. When we calculate the power of the cosine law from the intensities given by them for the various directions, we obtain the value 3.4. Again the sea-level measurements of Caro, Parry and Rathgeber<sup>16</sup> on the energy spectrum of  $\mu$ -mesons, gives for the *differential* spectrum an exponent  $3.0 \pm 0.2$  for energies greater than 20 Bev. This again would be consistent with an integral production spectrum of  $\pi$ 's with an exponent 1.8.

If we consider, in addition to  $\pi$ 's, the production of heavier short-lived mesons, then as pointed out already, the heavy mesons should be produced in as large a number as  $\pi$ 's and should directly decay into  $\mu$ -mesons with a life-time less than  $10^{-9}$  secs., if the discrepancy between the observed and calculated intensity-depth curves is to be removed. However, the existing results on the production of heavy mesons show that the ratio of production of  $\pi$ 's to  $K\mu$ 's is greater than 3, and that the life-time of  $K\mu$ 's is of the order of  $10^{-8}$  secs. The other possible explanation is that  $\pi$ -mesons do not interact with the same cross-section as protons. But recent experiments with photographic emulsions have shown that  $\pi$ -mesons do interact with a nuclear geometric cross-section upto  $10^{11}$  ev. There is no reason why the cross-section for the interaction should suddenly drop at higher energies.

Calculation shows that if about 5% of the mesons produced in nuclear interactions are  $\mu$ -mesons, or short-lived particles decaying into  $\mu$ -mesons, then the discrepancy mentioned above is removed to an appreciable extent. However, there is no conclusive experimental evidence either in favour or against such a hypothesis, at present.

#### SUMMARY

The production spectrum of the parents of the underground penetrating particles has been determined from a measurement of the angular distribution of the penetrating particles at a depth of 103 mwe. The results indicate a power-law production spectrum with an exponent  $-1.92 \pm 0.08$ .

This production spectrum has been used to deduce the theoretical intensity-depth curves for different compositions of the parents of  $\mu$ -mesons. A comparison of the theoretical curves with the composite intensity-depth curve leads to the following conclusions:

(a) The experimentally determined intensity-depth curve cannot be quantitatively explained, if  $\pi$ -mesons produced in the nuclear interactions of the primaries, are the only parents of  $\mu$ -mesons, and if they have the following properties:

- (i) the production spectrum is a power law with an exponent greater than 1.8.
- (ii)  $\pi$ -mesons decay into  $\mu$ -mesons with a life-time  $2.56 \times 10^{-8}$  secs.
- (iii)  $\pi$ -mesons interact with the same cross-section as the primaries.

(b) The production, in addition to  $\pi$ 's of other heavy mesons, which decay into  $\mu$ -mesons, will not remove the discrepancy between the observed and theoretical intensity-depth curves, unless these heavy mesons are produced in as large numbers as the  $\pi$ 's and have a life-time for  $\mu$ -decay less than  $10^{-9}$  secs.

Existing experimental evidence indicates a ratio not smaller than 3 for the ratio of production of  $\pi$ 's to heavy mesons and a life-time of the order of  $10^{-8}$  secs. for the decay of heavy mesons into  $\mu$ -mesons.

Calculation shows that the discrepancy is removed to a considerable extent if about 5% of the mesons produced in nuclear interactions are  $\mu$ -mesons or short-lived particles decaying into  $\mu$ -mesons. At present there is no experimental evidence either in favour or against such a hypothesis.

#### ACKNOWLEDGMENTS

We wish to express our gratitude to Prof. H. J. Bhabha, for suggesting the investigation, and for helpful discussions. We are highly indebted to Prof. Bernard Peters for valuable comments and discussions.

We wish to express our grateful thanks to Messrs. John Taylor & Sons, for according permission to carry out the experiments in the Mines at the Kolar Gold Fields. We are especially grateful to Mr. V. M. Sundararajan, and Mr. T. C. Barnett of Nundydroog Mines for taking a lively interest in the investigation, and for providing us with all the necessary facilities underground.

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