H. S. BRIDGE, H. C. DE STAEBLER jr., etc.
1956
N. 2 del *Supplemento* al Vol. 4, Serie X,
del *Nuovo Cimento* - pag. 552-556

Results on S Events.

Remarks on Range-Energy Relations.

H. S. BRIDGE, H. C. DE STAEBLER jr., B. ROSSI and B. V. SREEKANTAN
D. O. CALDWELL

Department of Physics and Laboratory for Nuclear Science
Massachusetts Institute of Technology - Cambridge, Mass.

At the request of the M.I.T. group, this paper was presented by B. P. GREGORY, who assumes responsibility, for any misquotation of their results.

Fig. 1.

In a recent paper [1] it was shown that the S-events obtained in the M.I.T. plate chamber represented decay processes of the type:

$$K_{\pi 2} \to \pi + \pi^0$$

$$K_{\mu 2} \to \mu + \nu \, .$$

The reader is referred to this paper for the details of the analysis. In Fig. 1 the experimental distribution of the stopping points of the charged secondaries are displayed in a histogram, and compared to the predicted distribution of stopping points *assuming that all events* correspond to a unique decay mode:

$$K \to \mu + \nu + \nu \, .$$

The calculated differential momentum spectrum $F(p)$ is corrected for the detection probability of the chamber which favors the observation of stopping points for μ's in the region of momentum 150 MeV/c. The corrected curve $W(p)$ is clearly incompatible with the experimental observation.

1. – Mass of $K_{\pi2}$ and $K_{\mu2}$.

In view of setting up a uniform procedure in range measurements for cloud chamber data, the mean range of the stopping secondaries was computed using the method given by ARMENTEROS *et al.* [2]. The changes in the values of the range limits given in [1] which result from this revision are negligible in all cases. The results are summarized in Table I for $K_{\pi2}$ and Table II for $K_{\mu2}$.

TABLE I. – *Summary of data for stopped secondaries from* $K_{\pi2}$*-mesons.*

Event	Mean range (g cm^{-2} of brass)	ΔR	Momentum (*) (MeV/c)	Δp
82203	42.4	3.3	199.8	6.8
92136	43.2	4.0	201.4	8.2
26110	44.6	3.1	204.3	6.4
87981	44.9	3.4	204.9	7.0
105596	44.9	2.4	204.9	4.9
Mean	44.2	1.4	203.5	2.8

(*) Using the range-energy relation of ARON, HOFFMAN and WILLIAMS. All errors are standard deviations.

TABLE II. – *Summary of data for stopped secondaries from* $K_{\mu2}$*-mesons.*

Event	Mean range (g cm^{-2} of brass)	ΔR	Momentum (MeV/c)	Δp
96787	72.2	3.6	225.3	5.9
85380	75.8	3.7	229.2	6.1
103309	77.7	2.9	231.3	4.8
92329	77.9	3.5	232.6	5.7
Mean	75.9	1.8	229.3	3.0

(*) Using the range-energy relation of ARON, HOFFMAN and WILLIAMS. All errors are the standard deviations.

The mean values for the ranges of the charged secondaries are

$$K_{\pi2} \qquad R = (44.2 \pm 1.4)\ \text{g cm}^{-2}\ \text{brass (*)}\,,$$
$$K_{\mu2} \qquad R = (75.9 \pm 1.8)\ \text{g cm}^{-2}\ \text{brass (*)}\,.$$

(*) The calculated difference of stopping power between brass and copper is of the order of .01 %.

The quoted errors are the statistical standard deviations and are derived from the errors of reconstruction, effects of multiple scattering, and range straggling. Another source of error could arise from the fact that one or more events could correspond to the decay in flight of a K-particle, and also, for the $K_{\pi 2}$, to possible nuclear collision losses of the secondary.

The effect on the mean range of possible decays in flight turns out to be small in our measurements. The smaller values of measured ranges correspond to events 96787, 82203 and 92136 in which the charged secondary was emitted in the forward direction in the laboratory system. The effect of a presumed decay in flight would in these cases tend to reduce the measured range. On the other hand the highest ranges measured could be in error due to a possible decay in flight (event 92329 and 105596). If one rejects arbitrarily these two events from the data, the effect on the range is (-0.6) for $K_{\mu 2}$ and (-0.4) for $K_{\pi 2}$.

The 5 events of Table I show such a good grouping that the effect on the mean of assuming one of the π secondaries has suffered some supplementary nuclear energy loss would be negligible. Nevertheless the error on the mean would then be higher, and one may estimate it by suppressing the most accurate measurement: the error on the range of the $K_{\pi 2}$ would then be ± 1.7 g cm^{-2} of brass.

The mass of the K-particle responsible for these two decay modes may then be obtained using the following data:

Particle	Rest Energy (MeV)
p	938.17
π^+	139.5
π^0	135.0
μ^+	105.5
e	0.511
ν	0.000

and the range energy relation of **Aron**, **Hoffmann** and **Williams** [3]. This curve is computed assuming a constant ionization potential $I = 333.5$ eV.

The results are:

$$\text{Mass } K_{\mu 2} = (943 \pm 14)\ m_e\,,$$

$$\text{Mass } K_{\pi 2} = (960 \pm 12)\ m_e\,..$$

2. – Comparison with E.P. data. Effect of the range-energy relation used.

In view of the similarity of methods used at E.P. and M.I.T. one may summarize the results of both laboratories including in the errors the best estimate of systematic errors due to the possibility of decay in flight and nuclear energy loss (for $K_{\pi 2}$).

The results on the masses are summarized in Table III using the Aron, Hoffmann and Williams curves for the second column as was done in [1] and [2] and a different range energy curve computed with an ionization potential 377 eV for the third column.

TABLE III.

	Range ($g\ cm^{-2}$ Cu)	Mass of primary ($I_{Cu} = 333.5$ eV) (m_e)	Mass of primary ($I_{Cu} = 377$ eV) (m_e)
MIT EP $K_{\mu 2}$	75.8 ± 1.5	942 ± 9	934 ± 9
MIT $K_{\pi 2}$	44.2 ± 1.7	960 ± 12	955 ± 12
Direct mass measurements (EP)	All events (22 events)	928 ± 20	938 ± 20
	$K_{\mu 2}$ (6 events)	906 ± 31	916 ± 31

The errors on the direct mass are quoted including the possible systematic error indicated in [2].

The errors on the ranges are computed according to the discussion in [2] and to the remarks made in the first part of this talk.

In order to evaluate the variation of the range energy relations for copper as a function of I we used the two points: $I = 309.9$ and $I = 333.5$ as computed by W. A. Aron, *University of California Thesis* [4] and Aron, Hoffmann and Williams.

3. – Remarks on range-energy relations.

It is quite clear from Table III that the main uncertainty in the masses of K_{π_2} and K_{μ_2} lies in the choice of the range-energy relations that are used in computing the momenta of secondary π's or μ's.

The two sets of masses quoted both correspond to an assumed constant value of the ionization potential. Since no experimental point exists at energies comparable to those at which the curves are used in our mass measurements, it is necessary to reexamine the available experimental data at low energy in order to see if a reasonable extrapolation method can be chosen.

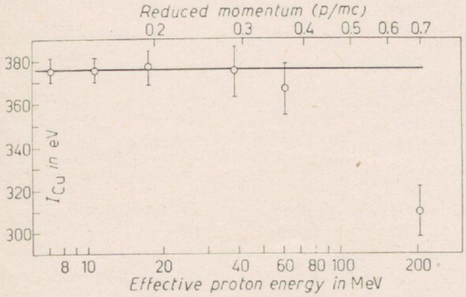


Fig. 2.

This study (*The Range Energy-Relation and Masses of the New Particles*, D. O. CALDWELL, to be published in the *Physical Review*) has been made and gives for copper the results of Fig. 2. In this figure the ionization potentials in copper for protons of various energies are plotted. The experimental points are those of SACHS and RICHARDSON [5], BLOEMBERGEN and VAN HEERDEN [6], BICHSEL and MOSLEY [7], for the low energy region and the measurement of MATHER and SEGRÈ [8] for high energy protons.

The aspect of the data shows the following:

All experimental points at very low energies are consistent with a constant $I_{Cu} = 377$ eV. The only point at high energy gives a value of $I_{Cu} = 310$ eV.

It is therefore clear that the Aron, Hoffmann, Williams curve using a constant $I_{Cu} = 333.5$ and which has been used both by M.I.T. and E.P. in reducing their data is incorrect in that it fits neither the low energy nor the high energy determination of I_{Cu}. Therefore the values of the masses derived from this curve must be affected by a systematic error. It is more difficult to predict what best value should be used. If one wants to preserve the *same shape* for the curve (I_{Cu} = constant) then the best value for the ionisation potential is 377 eV and the corresponding revised values of the masses are shown by Table III.

REFERENCES

[1] H. S. BRIDGE, H. DE STAEBLER jr., B. ROSSI and B. V. SREEKANTAN: *Nuovo Cimento*, **1**, 874 (1955).

[2] R. ARMENTEROS, B. GRÉGORY, A. HENDEL, A. LAGARRIGUE, L. LEPRINCE-RINGUET, F. MULLER and C. PEYROU: *Nuovo Cimento*, **1**, 915 (1955).

[3] W. A. ARON, B. G. HOFFMANN and F. C. WILLIAMS: *A.E.C.U.* 663 (1949).

[4] W. A. ARON: *U.C. Thesis UCRL*, 1325 (1951).

[5] D. C. SACHS and J. R. RICHARDSON: *Phys. Rev.*, **89**, 1163 (1953).

[6] N. BLOEMBERGEN and P. J. VAN HEERDEN: *Phys. Rev.*, **83**, 561 (1951).

[7] H. BICHSEL and R. F. MOSLEY: *Phys. Rev.*, **94**, 764 (A) (1954) and private communication.

[8] R. MATHER and E. SEGRÉ: *Phys. Rev.*, **84**, 191 (1951).

H. S. BRIDGE, H. C. DE STAEBLER jr., etc.
1956
N. 2 del *Supplemento* al Vol. **4**, Serie X,
del *Nuovo Cimento* - pag. 552-556

Reprinted from THE PHYSICAL REVIEW, Vol. 103, No. 1, 240–243, July 1, 1956
Printed in U. S. A.

Angular Correlation in New Unstable Particle Decays*

B. V. SREEKANTAN,† G. SANDRI, AND A. PEVSNER
Department of Physics and Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts

(Received March 9, 1956)

Among the cosmic-ray events recorded with a multiplate cloud chamber there are twelve in which two of the new unstable particles (hyperons or heavy mesons) seem to originate in the same nuclear interaction inside the chamber. Seven events show two neutral V particles, four show one neutral and one charged V, and one a neutral V and an S particle. The histogram of the dihedral angle between the production and decay planes of the unstable particles is found to be consistent with a uniform distribution. This result does not necessarily imply small spin for the new unstable particles.

I. INTRODUCTION

ONE of the fundamental properties of a particle is its spin. The determination of this quantity for hyperons and heavy mesons (here called collectively: "new unstable particles") is as yet an unsolved problem. It is of interest, in particular, to ascertain whether some of the "new unstable particles" have spin greater than $\frac{1}{2}$.[1]

A natural approach to the problem[2] is suggested by the fact that in reactions responsible for the production of the new unstable particles such as

$$\begin{aligned} \pi^- + p &\rightarrow \Lambda^0 + \theta^0, \\ \pi^+ + n &\rightarrow \Lambda^0 + K^+, \end{aligned} \tag{1}$$

the dihedral angle ψ between the planes of production and of decay[3] of the unstable particles is closely analogous to the angle employed to study the polarization of particles in double-scattering experiments. If the measured distribution of ψ, $F(\psi)$, shows a definite asymmetry, then among the hyperons and heavy mesons there are particles with spin greater than $\frac{1}{2}$.[4]

In reactions of the type observed in a multiplate cloud chamber,

$$(\pi \text{ or nucleon}) + (\text{nucleus}) \rightarrow V_a + V_b + (\text{other charged and neutral secondaries}), \tag{2}$$

the heavy nucleus may seriously affect the presumed correlation between production and decay planes, for the following reasons: (a) a considerable amount of angular momentum may be carried away by the residual nucleus, and the secondaries of the reaction other than the unstable particles; (b) the new unstable particles may be produced plurally or indirectly;[5] (c) the new unstable particles may be scattered before they decay because of strong interactions with the nucleons.[6]

Since the energy of the primary particle is very large compared with the binding energy of the nucleons, reactions of type (2) may nevertheless yield information on the correlations. It is easy to see the necessary conditions for the simple reactions (1) to have occurred. Since in (1) the lines of flight of the primary and those of the two unstable particles must be coplanar, we must have

$$\psi = \chi, \tag{3}$$

where ψ is the polarization angle and χ is the dihedral angle between the plane determined by the lines of flight of the two unstable particles, and the plane that contains the lines of flight of one of the unstable particles and either of its decay products.[7]

As a consequence of conservation of energy and momentum, we must also have

$$\left.\begin{array}{l} \phi_{\text{lab}}(\Lambda^0) < 57^\circ \\ \phi_{\text{lab}}(\theta^0) \text{ unrestricted} \end{array}\right\}, \tag{4}$$

where ϕ is the angle that the line of flight of the V^0

---

* This work was supported in part by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.

† On leave of absence from Tata Institute of Fundamental Research, Bombay, India.

[1] See the discussion by M. Gell-Mann and A. Pais in *Proceedings of the Glasgow Conference* (Pergamon Press, London, 1955). It would be of theoretical interest to find particles with spin $\geqslant 1$ in view of the renormalization difficulties encountered there. It may also be noted that the existence of a spin (and isotopic spin) $\frac{3}{2}$ isobar of the nucleon, which is suggested by the resonances in the π-nucleon scattering and photomesonic cross sections, may be closely related to the existence of the "new unstable particles." See H. Bethe and F. de Hoffmann, *Mesons and Fields* (Row, Peterson and Company, Evanston, 1955), p. 192 ff. Also, a knowledge of spins would shed light on the identity of the θ and τ mesons.

[2] Other methods have been suggested by S. Treiman, and by R. Karplus and M. Ruderman (to be published).

[3] The plane of production is determined by the lines of flight of the bombarding particle and of the unstable one. The plane of decay is determined by the lines of flight of the unstable particle and that of either of its charged secondaries.

[4] The angular distributions are discussed by E. Eisner and R. G. Sachs, Phys. Rev. **72**, 680 (1947); L. Wolfenstein, Phys. Rev. **75**, 1664 (1949); Treiman, Reynolds, and Hodson, Phys. Rev. **97**, 244 (1955); S. Treiman and H. Wyld, Phys. Rev. **100**, 879 (1955); R. Adair, Phys. Rev. **100**, 1540 (1955); L. P. Puzikov and Ia.A. Smorodinskii, Doklady Akad. Nauk. U.S.S.R. **104**, No. 6, 843 (1955) (translation by M. D. Friedman, 572 California Street, Newtonville 60, Massachusetts).

[5] Besides the possibility of successive production of the unstable particles in the nucleus (plural production), both unstable particles could be produced by particles other than the visible primary (indirect production).

[6] The possible importance of scattering has been noted in connection with the energy spectrum of the hyperons by G. James and R. Salmeron, Phil. Mag. **46**, 377, 571 (1955).

[7] This definition extends to $V^0 - V^{\text{ch}}$ events the angle used by Ballam, Hodson, Martin, Rau, Reynolds, Treiman, Phys. Rev. **97**, 244 (1955).

forms with the line of flight of the primary of the interaction.[8]

In an attempt to determine the possible asymmetry of $F(\psi)$ we have analyzed twelve reactions of the general type (2) produced in the Massachusetts Institute of Technology cloud chamber by energetic cosmic rays.[9] It is seen from Tables I and II that Eq. (3) is satisfied in five of the twelve events presented and that all but one of the events satisfies Eq. (4).

II. SELECTION OF THE EVENTS AND IDENTIFICATION OF THE UNSTABLE PARTICLES

We discarded for one of the following reasons seven of the nineteen M.I.T. events that show more than one unstable particle: (a) the only possible origin of the unstable particles is outside the chamber; (b) none of the nuclear interactions visible inside the chamber can be identified as the origin of the unstable particles without leaving one of the transverse momenta unbalanced; (c) the secondary prongs of each V are too short to permit a determination of the Q value. In the twelve events reported, there is only one possible origin common to the two unstable particles inside the chamber.

TABLE I. Data on double V^0 events. N_s—number of visible charged secondaries produced with the unstable particles. δ—angle of uncoplanarity of the V. ϕ—angle between the primary of the interaction and the unstable particle. ψ—dihedral angle between the production and decay planes of the unstable particle. χ—dihedral angle between the plane formed by the lines of flight of the two V's and the decay plane of the unstable particle.

Serial No.	N_s	δ(deg)	ϕ(deg)	ψ(deg)	χ(deg)	Q(Mev), remarks
26 194	9	1.6	56	9	9	<41, probable Λ^0.
		10	28	70	70	Cannot be identified.
27 429	1	3.5	22	59	11	>81 if θ^0, cannot be Λ^0.
		4.2	81	57	37	Cannot be identified.
32 659	2	1.5	56	67	40	Cannot be identified.
		3.6	35	1	49	31–73Λ^0. Cannot be θ^0.
3872*x*	2	3	14	74	9	33Λ^0. Cannot be θ^0.
		13	38	44	62	Cannot be Λ^0.
64 844	0	3.7	79	19	19	24–49Λ^0.
		1.0	35	57	51	Cannot be identified.
94 328	6	4	32	1.5	33.5	<51Λ^0. Cannot be θ^0.
		2	145	55	33.5	>199θ^0. Cannot be Λ^0.
103 075	1	2	29	33	61	26–27Λ^0. Cannot be θ^0.
		0	46	34	70	>101θ^0. Cannot be Λ^0.

TABLE II. Data on double V's: V^0+V^{ch}. The symbols are those employed in Table I.

Serial No.	N_s	δ(deg)	ϕ(deg)	ψ(deg)	χ(deg)	Q(Mev), remarks
67060	6	V^0 0	38	28	76	30–81Λ^0
		V^{ch}	59	6	36	
87074	3	V^0 1	16	67	67	<45Λ^0
		V^{ch}	27	14	10	
96787	5	V^0 2	141	54	54	18–53Λ^0
		S	136			$K_{\mu 2}$ (72–85 g range, Br)
98163	8	V^0 4	32	27	27	18–71Λ^0
		V^{ch}	19	12	12	
95829	9	V^0 4.7	···	···	38	<50Λ^0
		V^{ch}	···	···	24	(produced by neutral primary)

The V^0 particles have been analyzed assuming the following decay schemes:

$$V^0 \rightarrow p+\pi^-, \tag{5}$$

$$V^0 \rightarrow \pi^+ + \pi^-. \tag{6}$$

A V^0 which, when analyzed according to scheme (5), gives a Q value compatible with 37 Mev is identified as a probable Λ^0. A V^0 which, when analyzed according to scheme (6), gives a Q value compatible with 214 Mev is identified as a probable θ^0. In many events it is possible to say that the V^0 is not a Λ^0 (or a θ^0) from considerations of residual range, ionization, and inferred transverse momentum of the charged secondaries.

It is unfortunate that the identity of the V^{ch} particles cannot be established. In the four events analyzed, the charged secondary forms a large angle ω with the line of flight of the V^{ch} and leaves the chamber without penetrating any plates. From an estimate of the ionization of the V^{ch} and the measured angle ω we can conclude that in three of the four V^0-V^{ch} events (the exception being 95 829), the unstable particle can be neither a π decaying into a μ meson nor a hyperon decaying into a proton. It is not possible to say whether the V^{ch} particles are heavy mesons decaying into π's or μ's or hyperons decaying into π mesons. The S particle in event 96 787 is most probably a $K_{\mu 2}$ since its secondary has a range between 72 and 85 g cm^{-2} of brass.

It is difficult to determine exactly the error involved in angular measurements. Our estimate is that for all the angles discussed the error is between 2 and 4 degrees.[10]

III. SUMMARY OF RESULTS

The number of charged secondaries, the angles, and the Q values are given in Tables I and II.

---

[8] A detailed analysis of the dynamics of reaction (1) is found in reference 5.

[9] The chamber is described by Bridge, Peyrou, Rossi, and Safford, Phys. Rev. **90**, 921 (1953). The plates in this chamber are brass or lead. Our cases do not indicate that the type of nucleus in Eq. (2) is relevant for the angular distributions discussed.

[10] See the discussion by Bridge, Peyrou, Rossi, and Safford, Phys. Rev. **91**, 362 (1953).

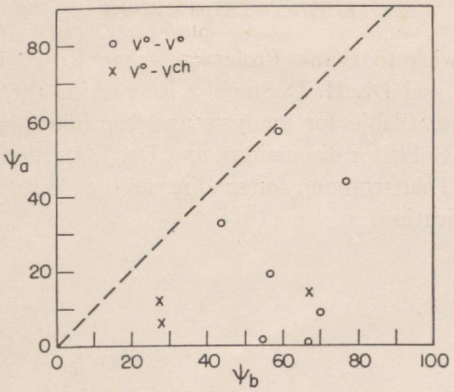


FIG. 1. Distribution of 10 double-V events in the $\psi_a-\psi_b$ plane ($\psi_a<\psi_b$ in degrees).

We note some general features of the events considered.

(i) The number of visible prongs that emerge from the interaction presumably responsible for the production of the unstable particles ranges from 0 to 9. These prongs do not seem to lie preferentially in a plane.

(ii) The V^0 particles that have been identified as probable Λ^0 (with the exception of 96 787) have angles of production in the laboratory frame of reference, ϕ_{lab}, smaller than 60°.[11]

(iii) Event 64 844 is likely to represent a reaction of type (1):

$$(\text{charged primary})+(\text{nucleon})\rightarrow\Lambda^0+\theta^0.$$

Since no charged prong is seen to come from the interaction in spite of the fact that the origin of the V's is in the well-illuminated region of the chamber and about one millimeter above the bottom of a plate. Also $\psi=\chi$ for both V's. It is probably accidental that $\psi=\chi$ in event 26 194 since $N_s=9$ and for one of the V's $\delta=10°$.

(iv) In two of the three V^0-V^{ch} events for which comparison is possible, $\psi=\chi$ within the experimental uncertainty. In the V^0-S event, we also find $\psi=\chi$.

(v) To understand the behavior of ψ and χ, we have plotted in Fig. 1 the ψ_a *versus* the ψ_b corresponding to the two unstable particles contained in each event and in Fig. 2 χ_a *versus* χ_b. The conventions $\psi_a<\psi_b$, $\chi_a<\chi_b$ are used with the consequence that the experimental points lie all on the same side of the 45° line. Only Fig. 2 includes events reported by other groups[12] since usually χ but not ψ is given. No tendency towards a clustering of the points is found. Figure 3 is a histogram of the ψ for 32 events (including our "single V's)."[11] Fitting to the theoretical curves gives no evidence for spin greater than $\frac{1}{2}$.

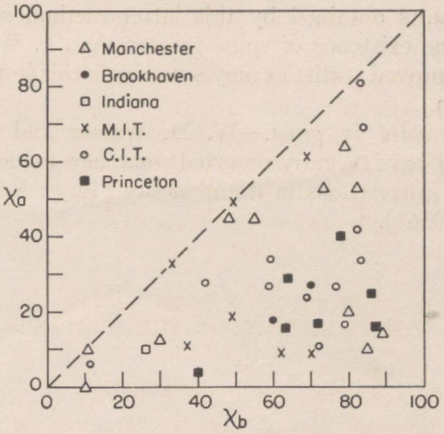


FIG. 2. Distribution of events in $\chi_a-\chi_b$ plane for 40 double-V^0 events reported by various groups ($\chi_a<\chi_b$ in degrees).

IV. CONCLUDING REMARKS

Our results may be summarized as follows: the presence of prongs indicates the complexity of the reactions discussed; a number of the events considered satisfy the conditions for an elementary reaction [Eqs. (3) and (4)]; within the statistics the observed distributions of ψ and χ are uniform.

Clearly one cannot combine the statements above to infer that all the "new unstable particles" have spin less than 1 mainly because a heavy nucleus rather than a nucleon is the target of the reactions analyzed. Inelastic collisions of π mesons with hydrogen nuclei, recently studied at Brookhaven, obviate this difficulty.[13]

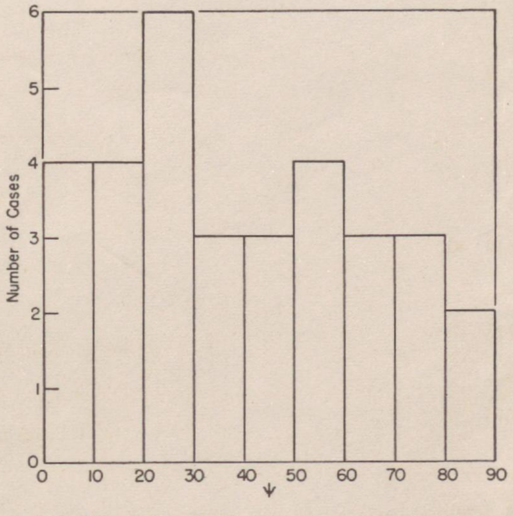


FIG. 3. Dihedral angle (degrees) between production and decay planes of 32 V^0 events.

---

[11] The histogram of ϕ_{lab} for all identified V^0 [including the single V's previously reported by us, Phys. Rev. **99**, 642(A) (1955)] indicates a peak at about 30°. For a further discussion of this distribution, see R. Jastrow, Phys. Rev. **97**, 181 (1954).

[12] J. Ballam *et al.*, reference 7; G. James and R. Salmeron, reference 6; J. D. Sorrells, private communication; Thompson, Burwell, Huggett, and Karzmark, Phys. Rev. **95**, 1576 (1954). See also forthcoming papers by N. Deutschmann, M. Cresti, W. Greening, L. Guerriero, A. Loria, G. Zago, W. D. Walker, and W. D. Sheperd.

[13] Fowler, Shutt, Thorndike, and Whittemore, Phys. Rev. **91**, 1287 (1953); **93**, 861 (1954); **98**, 121 (1955).

The results obtained by this latter method seem to favor the existence of spins greater than $\frac{1}{2}$. We hope that improved statistics may soon settle this important question.

Note added in proof.—W. D. Walker and W. D. Shepard have recently reported some new evidence for angular correlations in the Λ^0 decay [Phys. Rev. **101**, 1810 (1956)].

ACKNOWLEDGMENTS

We wish to thank Professor Bruno Rossi, Dr. H. Bridge, and Dr. H. DeStaebler for making the photographs available for analysis and continued interest, Mr. E. Boldt for discussions, and Dr. J. D. Sorrels and Dr. N. Deutschmann for sending us their results prior to publication.

S. Naranan

Reprinted from the "Proceedings of the Indian Academy of Sciences," Vol. XLIII, 1956

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

BY

B. V. SREEKANTAN, S. NARANAN AND P. V. RAMANAMURTY

Reprinted from "The Proceedings of the Indian Academy of Sciences", Vol. XLIII, No. 2, Sec. A, 1956

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

By B. V. Sreekantan, S. Naranan and P. V. Ramanamurty

(*Tata Institute of Fundamental Research, Bombay*)

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[1(a)–(e)] upto a maximum depth of about 3,000 metres water equivalent (mwe). Barrett *et al.*[2] 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[3]* 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 μ-meson, makes it quite certain that the underground penetrating particles are essentially the high energy μ-mesons encountered at sea-level.

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

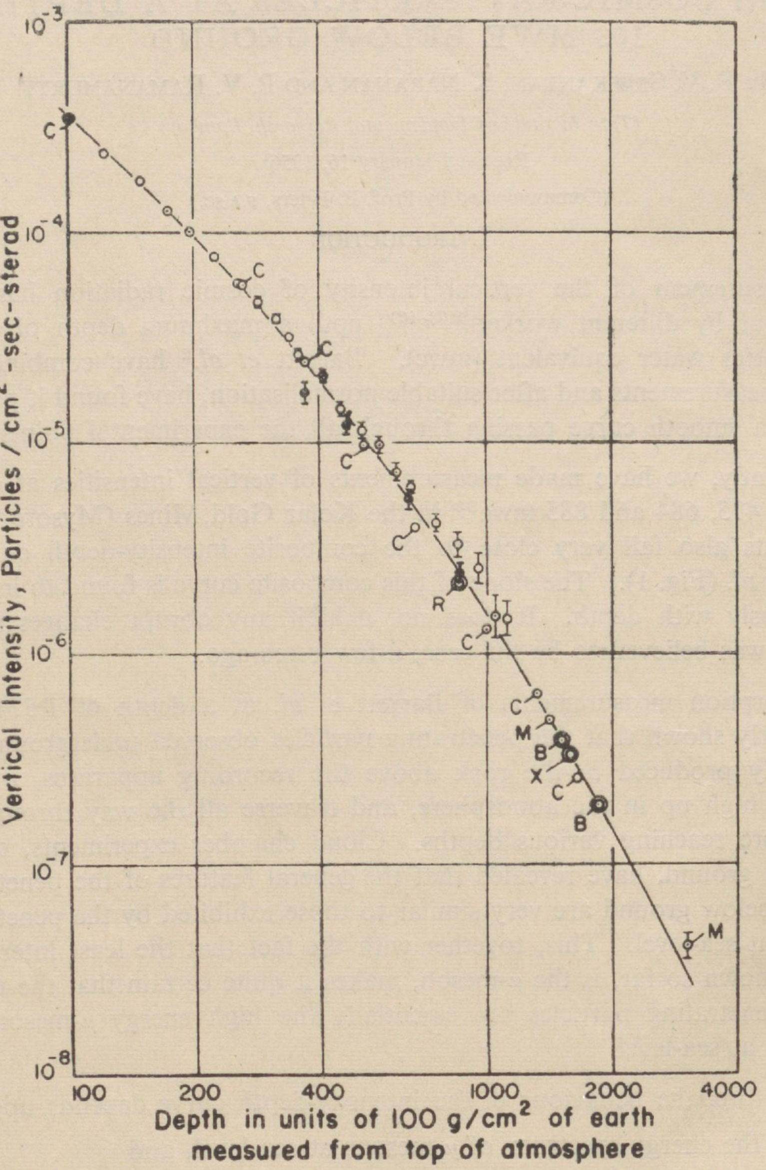
(*a*) the energy spectrum of μ-mesons at sea-level, and

(*b*) the range-energy relation of μ-mesons.

---

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

It is well known that μ-mesons are not produced directly in nuclear interactions. They are the decay products of heavier mesons. Therefore, the sea-level spectrum of μ-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 μ-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 μ-mesons have been established, *viz*., the π-mesons and some of the K-mesons. The mass, life-time and absorption mean free path of π-mesons are very well established. The properties of K-mesons are however not so well determined yet. Among the K-mesons, which decay into μ-mesons, two types have been recognised.

(*a*) the K_{μ_2}, which undergoes decay according to the two-body decay scheme

$$K_{\mu_2} \rightarrow \mu + \nu \text{ and}$$

(*b*) the K_{μ_3}, or the kappa-meson which decays according to the three-body decay scheme

$$K_{\mu_3} \rightarrow \mu + ? + ?$$

Evidence for K_{μ_2}, undergoing a two-body decay, was first obtained by the Ecole Polytechnique group.[4] Bridge *et al.*[5a] measured the range of μ-mesons emitted by K_{μ_2} mesons stopped in a multi-plate cloud chamber, and deduced the mass of K_{μ_2} as $950 \pm 15\, m_e$. From direct measurements on K_{μ_2} particle, as well as measurement of the range of the secondary μ-meson, Armenteros *et al.*[5b] 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,[6] and Barker *et al.*[7] indicate that the K_{μ_2} life-time is of the order of 10^{-8} secs.

Evidence for K_{μ_3} or kappa mesons was first found by Menon and O'Ceallaigh[8] in photographic emulsions. Direct evidence for the three-body decay scheme involving a μ-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 μ-mesons by μ-e decay. The best estimate of the mass of K_{μ_3} is $1035 \pm 25\, m_e$.[9] Armenteros *et al.*[10] give a life-time of the order of 10^{-9} secs. for K_{μ_3} particles. The relative abundance of K_{μ_2} and K_{μ_3} is not well known. An absolute upper limit to the ratio of charged heavy mesons to charged π-mesons, produced at very high energies, is deduced to be 25%.[11]

At low energies all the π and K_μ-mesons decay into μ-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 μ-mesons at the high energy end. Using the decay and absorption constants, it is possible to work out theoretically, the sea-level μ-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 μ-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 μ-mesons with an exponent $-1 \cdot 92 \pm 0 \cdot 08$.

In Section III, we have calculated the theoretical intensity-depth curves for different conditions of production of the parents of μ-mesons and also using different range-energy relations of μ-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 μ-MESONS AND THE PRODUCTION SPECTRUM OF PARENTS OF μ-MESONS

Let us consider, for the present, the production of π-mesons alone in the nuclear interactions of the primaries. The π-mesons are known to decay with a life-time $2 \cdot 56 \times 10^{-8}$ secs. into μ-mesons. There is now substantial evidence to show that the π-mesons[12] 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 π-mesons, it is easy to derive (see Barrett *et al.*) the following expression for the sea-level intensity of μ-mesons arriving at an angle θ with respect to the vertical, with an energy greater than E_θ at production:

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

where E_θ = minimum energy of the μ-mesons at the production layer.

ϵ = the exponent in the integral spectrum of π-mesons at production, assumed to follow a power law.

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

$m_\pi c^2$ = rest energy of π-mesons = $0{\cdot}140$ Bev.

γ_π = energy degradation factor in π-μ decay = $0{\cdot}76$.

τ_π = mean life-time of π-mesons = $2{\cdot}56 \times 10^{-8}$ secs.

H = equivalent atmospheric depth in cm. = $6{\cdot}46 \times 10^5$ cm.

K_π = a constant.

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

$$E = \alpha \,.\, R \tag{2}$$

where R is the range of μ-mesons in mwe, and α is a constant giving the rate of loss of energy per mwe.

The minimum energy E_θ that a μ-meson should have at the top of the atmosphere, in order to arrive at a depth D, at an angle θ with respect to the vertical,

$$E_\theta = \alpha R_\theta \tag{3}$$

where R_θ is the amount of matter encountered by the μ-meson in the direction θ and is given by

$$R_\theta = D/\cos\theta. \tag{4}$$

From (3) and (4),

$$E_\theta = \alpha D/\cos\theta. \tag{5}$$

Substituting the expression for E_θ given by (5) in (1), we obtain the expression for the intensity of μ-mesons arriving at an angle θ with respect to the vertical, at a depth D mwe below the top of the atmosphere,

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

$$= \text{constant.}\ \cos^\epsilon\theta \tag{7}$$

since γ_π, τ_π, D, B_π and ϵ are all constants. Therefore, the exponent in the cosine law for the angular distribution of underground μ-mesons gives the exponent in the generation spectrum of π-mesons.

Let us now take into consideration the production of K_μ-mesons as well. If the production spectrum of K_μ's and π's follow the same power law, then from an exactly similar treatment as above, we have

$$\mathrm{I_D}(\theta) = \mathrm{K}_\pi\left(\frac{\gamma_\pi \cos\theta}{\alpha \mathrm{D}}\right)^\epsilon \frac{\mathrm{B}_\pi}{(\epsilon+1)\,\alpha\mathrm{D} + \epsilon\mathrm{B}_\pi + \dfrac{\sqrt{\mathrm{B}_\pi \alpha \mathrm{D}}}{2\epsilon+1}}$$

$$+ \mathrm{K}_k\left(\frac{\gamma_k \cos\theta}{\alpha \mathrm{D}}\right)^\epsilon \frac{\mathrm{B}_k}{(\epsilon+1)\,\alpha\mathrm{D} + \epsilon\mathrm{B}_k + \dfrac{\sqrt{\mathrm{B}_K \alpha \mathrm{D}}}{2\epsilon+1}}$$

$$= \text{constant.}\quad \cos^\epsilon\theta.$$

where K_k, B_k, m_k, γ_k and τ_k are constants referring to K_μ-mesons.

Therefore, *provided the production spectrum of K_μ-mesons and π-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 μ-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[13] 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:

$$\mathrm{R}' = 1/b \ \ln(1 + b\mathrm{E}/d) \qquad (8)$$

where R' is the range of μ-mesons expressed in gm. cm.$^{-2}$ and E is the energy of the μ-mesons expressed in Mev. $b = 5 \cdot 26 \times 10^{-6}$ for rock of mean atomic number 10·5 and mean atomic weight 21. $d = 2 \cdot 65$ Mev. gm.$^{-1}$ cm.$^{-2}$

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 θ varying from 0° to 75° 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°.

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 μ-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.

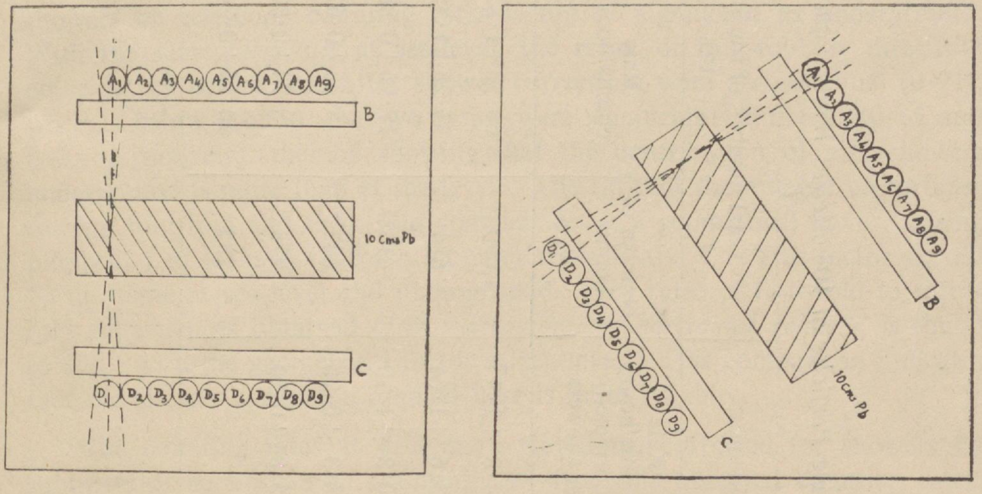


FIG. 2. Counter telescope used for the angular distribution experiment.

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°, 45°, 60°, 65°, 75° and 90° 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 ($i = 1 \ldots\ldots 9$)

(*b*) three-fold coincidence rates $A_i BD_i$ ($i = 1 \ldots\ldots 9$)

(*c*) three-fold coincidence rates $A_i CD_i$ ($i = 1 \ldots\ldots 9$)

and (*d*) four-fold coincidence rates $A_i BCD_i$ ($i = 1 \ldots\ldots 9$)

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°. 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 θ 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 $1{\cdot}92 \pm 0{\cdot}08$. Therefore, the angular distribution at a depth of 103 mwe can be expressed by the cosine law,

$$\mathrm{I}(\theta) = \mathrm{I}(0) \cos^{1\cdot 92 \pm 0\cdot 08}\theta$$

or *the exponent in the production spectrum of the parents of* μ*-mesons is* $-1{\cdot}92 \pm 0{\cdot}08$.

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

Using equation (1) in Section I, and the production spectrum $\mathrm{E}^{-1\cdot 92}$, we have worked out the theoretical intensity-depth curves, considering the production of π-mesons alone in nuclear interactions of primaries, and assuming

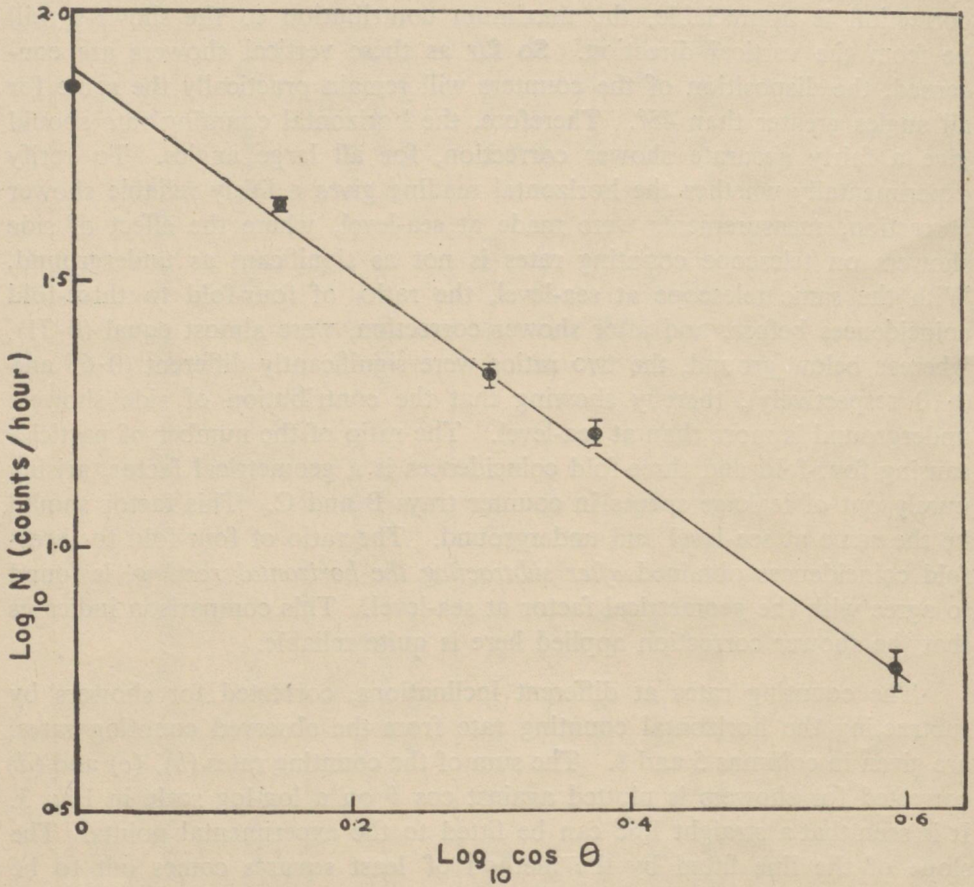


FIG. 3. Angular distribution of penetrating particles at 103 mwe.

(*a*) the range-energy relation of μ-mesons to be linear upto 300 Bev, and a constant energy loss of 2·2 Mev gm.$^{-1}$ cm.^{2}

(*b*) the range-energy relation given by George (equation 8 in Section II), which takes into account the various processes by which μ-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

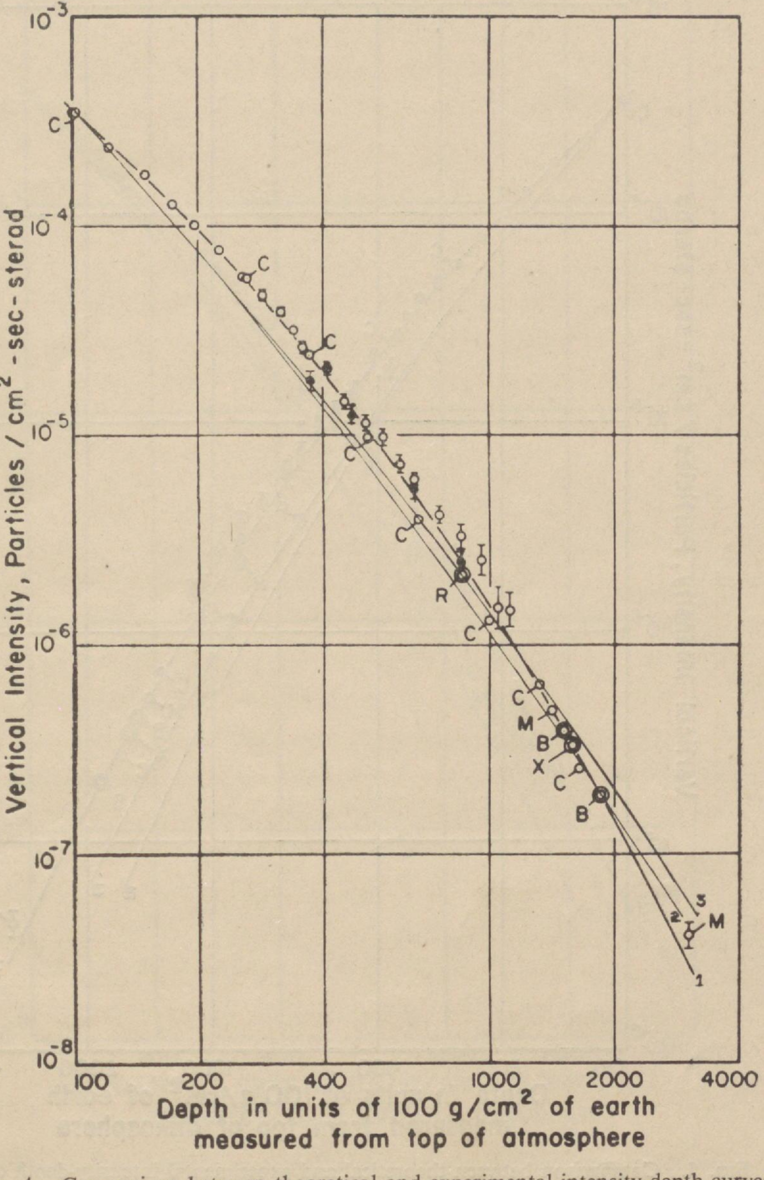


FIG. 4. Comparison between theoretical and experimental intensity-depth curves.

(1) Experimental intensity-depth curve.

Theoretical intensity-depth curves
with $\epsilon = 1\cdot92$. Linear range-energy relation (energy loss $= 2\cdot2$ Mev. gm.$^{-1}$) cm.^{2} and assuming

(2) Only π's are the parents of μ-mesons.

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

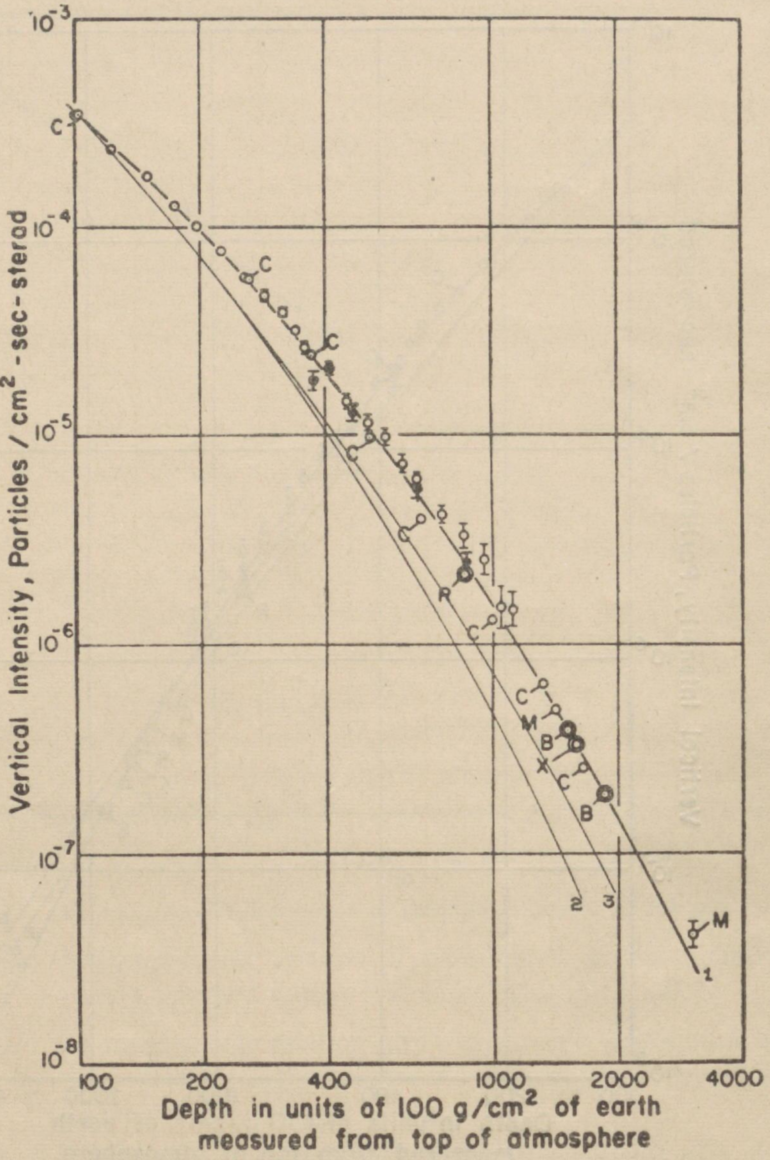


FIG. 5. Comparison between theoretical and experimental intensity-depth curves.

(1) Experimental intensity-depth curve.

Theoretical intensity-depth curves

with $\epsilon = 1 \cdot 92$ and assuming only π's are parents of μ-mesons, and George's range-energy relation (eq. 8).

(2) Including nuclear losses ($b = 5 \cdot 26 \times 10^{-6}$ in eq. 8).

(3) Excluding nuclear losses ($b = 2 \cdot 80 \times 10^{-6}$ in eq. 8).

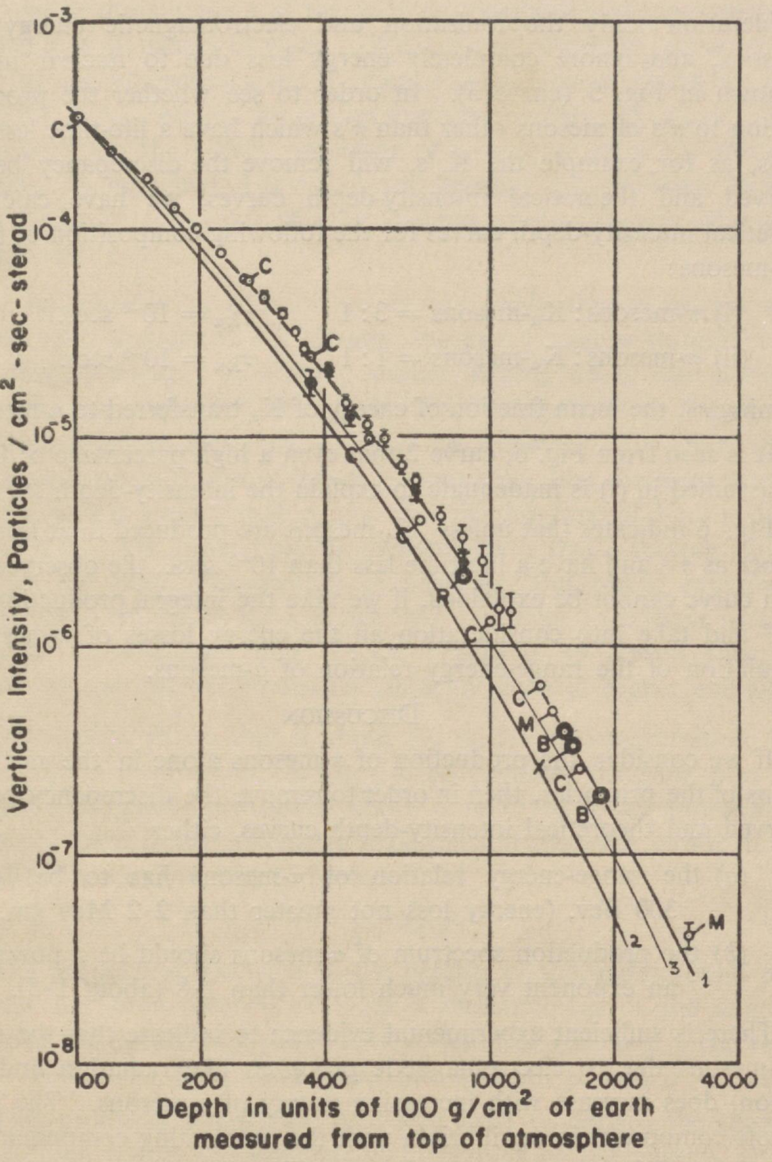


FIG. 6. Comparison between theoretical and experimental intensity-depth curves.

(1) Experimental intensity-depth curve.

Theoretical intensity-depth curves

with $\epsilon = 1{\cdot}92$ and assuming George's range-energy relation (eq. 8) and π's and $K\mu$'s are parents of μ'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 μ-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 π's of mesons other than π's which have a life-time less than that of π's, as for example the K_μ'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 μ-mesons:

(i) π-mesons : K_μ-mesons $= 3:1$ $\tau_{k\mu} = 10^{-8}$ secs.

(ii) π-mesons : K_μ-mesons $= 1:1$ $\tau_{k\mu} = 10^{-9}$ secs.

assuming r_k, the mean fraction of energy of K_μ transferred to μ-meson as 0·5.

It is seen from Fig. 6, curve 2 that even a high percentage of K_μ production assumed in (i) is inadequate to explain the intensity-depth curve. Curve 3 in Fig. 6 indicates that unless K_μ-mesons are produced in at least as large number as π'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 μ-mesons in the formulation of the range-energy relation of μ-mesons.

DISCUSSION

If we consider the production of π-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 μ-mesons has to be linear upto 300 Bev. (energy loss not greater than 2·2 Mev $\text{gm.}^{-1}\,\text{cm.}^2$).

or (*b*) the production spectrum of π-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 μ-mesons due to electromagnetic processes like radiation and pair production, does increase with increasing energy of μ-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 μ-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[14] working at a depth of 60 mwe, obtained for the power of the cosine law the value 2·02 ± 0·2. Quercia and Rispoli[15] 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[16] on the energy spectrum of μ-mesons, gives for the *differential* spectrum an exponent $3 \cdot 0 \pm 0 \cdot 2$ for energies greater than 20 Bev. This again would be consistent with an integral production spectrum of π's with an exponent 1·8.

If we consider, in addition to π'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 π's and should directly decay into μ-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 π'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 π-mesons do not interact with the same cross-section as protons. But recent experiments with photographic emulsions have shown that π-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 μ-mesons, or short-lived particles decaying into μ-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 $-1 \cdot 92 \pm 0 \cdot 08$.

This production spectrum has been used to deduce the theoretical intensity-depth curves for different compositions of the parents of μ-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 π-mesons produced in the nuclear interactions of the primaries, are the only parents of μ-mesons, and if they have the following properties:

(i) the production spectrum is a power law with an exponent greater than 1·8.

(ii) π-mesons decay into μ-mesons with a life-time $2 \cdot 56 \times 10^{-8}$ secs.

(iii) π-mesons interact with the same cross-section as the primaries.

(*b*) The production, in addition to π's of other heavy mesons, which decay into μ-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 π's and have a life-time for μ-decay less than 10^{-9} secs.

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

Calculation shows that the discrepancy is removed to a considerable extent if about 5% of the mesons produced in nuclear interactions are μ-mesons or short-lived particles decaying into μ-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.

REFERENCES

1. (*a*) Wilson, V. C. .. *Phys. Rev.*, 1938, **53**, 337.
   (*b*) Clay, J. and Gemert, A. *Physica*, 1939, **6**, 497.
   (*c*) Randall and Hazen, W. E. *Phys. Rev.*, 1951, **81**, 144.
   (*d*) Miyazaki, Y. .. *Ibid.*, 1949, **76**, 1733.
   (*e*) Bollinger, L. M. .. *Thesis*, Cornell Univ.
2. Barrett, P. H., Bollinger, L. M., Cocconi, C., Eisenberg, Y. and Greisen, K. I. *Reviews of Modern Physics*, 1952, **24**, 133.
3. Sreekantan, B. V. and Naranan, S. *Proc. Ind. Acad. Sci.*, 1952, **36**, 97.

4. Gregory, B., Lagarrigue, A., Leprince-Ringuet, L., Muller, F. and Peyrou, C. *Nuovo Cimento*, 1954, **11**, 292.

5. (*a*) Bridge, H. S., De Staebler, H. C., Rossi, B. and Sreekantan, B. V. *Ibid.*, 1955, **1**, 874.

(*b*) Armenteros, R., Gregory, B., Hendel, A., Lagarrigue, A., Leprince-Ringuet, L., Muller, F. and Peyrou, Ch. *Ibid.*, 1955, **1**, 915.

6. Robinson, K. .. *Bull. Am. Phys. Soc.*, 1955, **30**, 42.

7. Barker, P. R., Binnie, D. M., Hyams, B. D., Rout, R. J. and Shepherd, J. *Phil. Mag.*, 1955, **46**, 307.

8. Menon, M. G. K. and O'Ceallaigh, C. *Proc. Roy. Soc.*, 1954, **221**, 292.

9. Dilworth, C. C., Manfredini, A., Rochester, G. D., Waddington, J. and Zorn, G. T. "Report of the Committee on K-particles," *Nuovo Cimento Suppl.*, 1954, **12**, 433.

10. Armenteros, R., Gregory, B., Lagarrigue, A., Leprince-Ringuet, L., Muller, F. and Peyrou, Ch. *Ibid.*, 1954, **12**, 327.

11. Lal, D., Yash Pal and Rama *Proc. Ind. Acad. Sci.*, 1954, **39**, 127.

12. Rama .. *Ibid.*, 1954, **39**, 162.

13. George, E. P. .. *Progress in Cosmic Ray Physics*, Vol. I, Ch. VII, p. 395, Ed. by J. G. Wilson (North Holland Pub. Co., 1952).

14. Follet, D. H. and Crawshaw, J. D. *Proc. Roy. Soc.*, 1936, **155 A**, 546.

15. Quercia, I. F. and Rispoli, B. *Half-Yearly Report* (Autumn, 1951), Institute of Physics, Univ. of Rome.

16. Caro, D. D., Parry, J. K. and Rathgeber, H. D. *Nature* (London), 1950, **165**, 689.

BANGALORE
PRESS
LAKE VIEW
MYSORE RD
BANGALORE
CITY