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The Kolar Gold Fields neutrino experiment
II. Atmospheric muons at a depth of 7000 hg cm^{-2} (Kolar)

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An experiment has been performed in the Kolar Gold Fields in Southern India to search for the interaction products of cosmic ray neutrinos. In the course of four years operation of the detectors at a depth of 2316 m of rock, some 165 particles were recorded which were attributed to muons of atmospheric (as distinct from neutrino-) origin and the present paper describes the results of measurements on these particles.

The measured vertical intensity at the depth in question (2316 m of Kolar rock corresponding to 7.6×10^5 g cm^{-2} of standard rock) is (1.1 ± 0.2) 10^{-6} m^{-2} s^{-1} sr^{-1}. Including measurements at shallower depths by other workers, from sites elsewhere in the same Gold Fields, a best fit to the data gives the relation

$$I(h) = 7.73 \times 10^{-3} \exp(-h/790) \text{ m}^{-2} \text{ sr}^{-1} \text{ s}^{-1}$$

for depth range $4000 < h < 9500$ hg cm^{-2} Kolar rock (1 hg cm^{-2} = 10^2 g cm^{-2}).

An approximate estimate has been made of the mean energy of the atmospheric muons at the depth of operation; its value, *ca.* 330 GeV, is not inconsistent with the expected value.

1. INTRODUCTION

In the preceding part I (Krishnaswamy *et al.* 1971) we have given an account of the final results from the experiment that we have carried out deep underground in the Kolar Gold Fields on the detection of muons generated through the interactions of cosmic ray neutrinos in the rock surrounding our apparatus.

During the course of this experiment a considerable amount of data has also been accumulated on the intensity and angular distribution of atmospheric muons at the depth of observation, namely, 2316 m of Kolar rock. ($\langle \rho \rangle = 3.02$ g cm^{-2}, $\langle Z/A \rangle = 0.495$, $\langle Z^2/A \rangle = 6.3$; the depth corresponds to 7000 hg cm^{-2} of Kolar rock.) In previous reports (Menon *et al.* 1967*a, b*) we have given values of the vertical intensity of muons at this depth. There has been approximately a fourfold increase in the number of data on atmospheric muons since then. This has made it possible

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to obtain a direct measure of the angular distribution of atmospheric muons out to 45° from the zenith and thus to infer the variation of vertical intensity with depth to about 10000 hg cm^{-2} of rock.

2. THE DETECTORS

Experimental details relating to the location and the design and operation of the seven detectors of three distinct types (telescopes 1 and 2, telescopes 3 to 5 and spectrographs 1 and 2) that we employed have already been given in part I. An event is recorded when there is a pulse from one wall of scintillator in coincidence with the pulse from the other wall; this we refer to as a 'two-side trigger'. 'In-geometry' events correspond to cases where the penetrating particle itself traversed the two walls of plastic scintillator. However, in about one in six of the events recorded in telescopes 1 and 2 and the spectrographs there was no penetrating particle passing through two scintillator walls, and information from the neon flash tube arrays allowed these events to be recognised and eliminated. In about half of the rejected events a penetrating particle could be seen to pass through one of the scintillator walls and the coincidence trigger was generated by the accompanying electromagnetic component passing through the other wall. The other rejected events appeared to be the tail ends of electromagnetic cascades presumably initiated by muons passing close to the detectors. (The term 'wall' includes the top scintillators in the case of the spectrographs; the biggest contribution to the data comes from the spectrograph results, in fact.)

Telescopes 3 to 5 were first run with the same two side triggering requirement as for telescopes 1 and 2. This was later modified to one side triggering (o.s.t.) for reasons that we have described in part I. In this mode the gain of the photomultipliers had to be reduced in order to keep the rate of accidental coincidences low. This resulted in some loss of triggering efficiency. We have measured the triggering efficiency as a function of the angle of the particle trajectory with the normal to the plane of the scintillator in an experiment conducted at a shallow depth. It varies from 40 % for normal incident particles to greater than 99 % for particles incident at an angle of 70° or more to the scintillator normal. This variation of efficiency was taken into account when calculating the o.s.t. apertures. The correction is not very large for atmospheric muons since their angular distribution is strongly peaked in the vertical direction and most of them have therefore had long path lengths through the scintillator. The o.s.t. apertures were calculated with a vertical fiducial plane within the telescope at 19 cm from the scintillator wall for events where the muon traversed one or more flash tube arrays, and with a plane at 42.5 cm for events in which two or more trays were traversed. With the neon flash tubes the zenith angle, ϕ, of the incident muon projected on to a vertical plane, could be determined with an accuracy of about one degree.

3. THE EXPERIMENTAL DATA

As already discussed in paper I we consider all single penetrating particles traversing the detectors with projected zenith angle $\phi \leqslant 45°$ to be atmospheric muons. The total numbers of these events are given in table 1. The observed frequency distributions are presented in figures 1 to 3. In telescopes 1 and 2 all in-geometry particles must pass through the two layers of lead absorber. In the spectrographs the events are divided into two categories, those in which the track intersects the magnet and those in which it does not. In telescopes 3 to 5 operated on o.s.t. a track may pass through one to five trays of neon flash tubes depending on the zenith angle and the point of intersection with the scintillator. These events are again divided into two categories; those in which the track is seen in more than one flash tube tray, and is therefore known to have penetrated at least one layer of iron absorber, and those in which the track is seen only in the one tray nearest the scintillator. In the former case there is also information on the azimuth angle and hence the spatial zenith angle can be calculated.

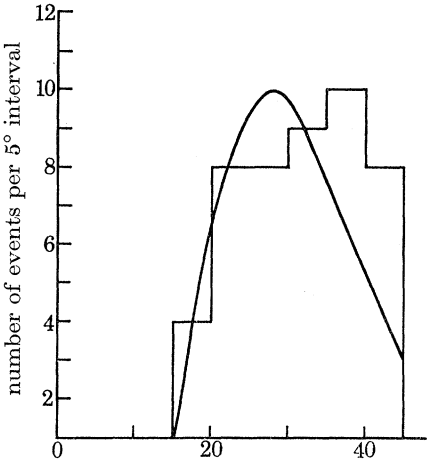


FIGURE 1

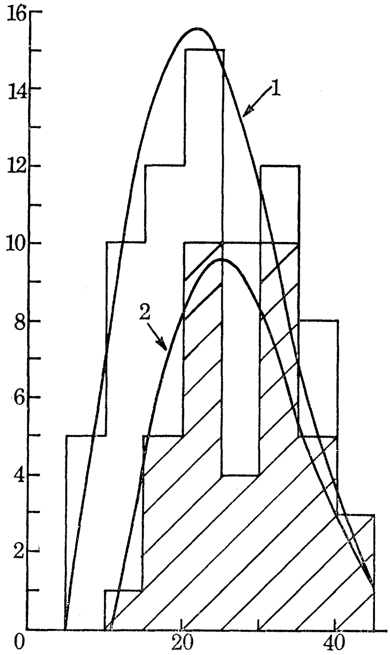


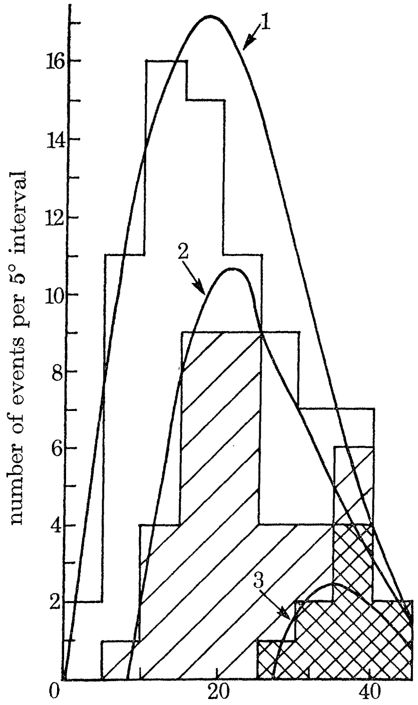
FIGURE 2

FIGURE 1. Angular distribution of events in telescopes 1 and 2 up to 45°. The lines in figures 1 to 4 are the predictions for $I(\theta, h) = 1.10 \times 10^{-6} \sec\theta \exp\{-9(\sec\theta - 1)\}\ \mathrm{m^{-2}\,s^{-1}\,sr^{-1}}$.

FIGURE 2. Angular distribution of events in telescopes 3 to 5 (o.s.t.) up to 45°. □, One tray only; ▨, more than one tray. Line 1 is the prediction for all events. Line 2 is the prediction for events passing through more than one tray.

3.1. *The angular distribution of atmospheric muons*

In figure 4 the combined angular distribution of all seven detectors is given. In this figure, o.s.t. events seen in one tray only have been omitted owing to the possibility that some of these events, in which the observed particle passes through no absorber, may conceivably be due to electrons accompanying muons that pass close to the detector rather than the muons themselves; in these cases there is also ambiguity in defining the aperture accurately.



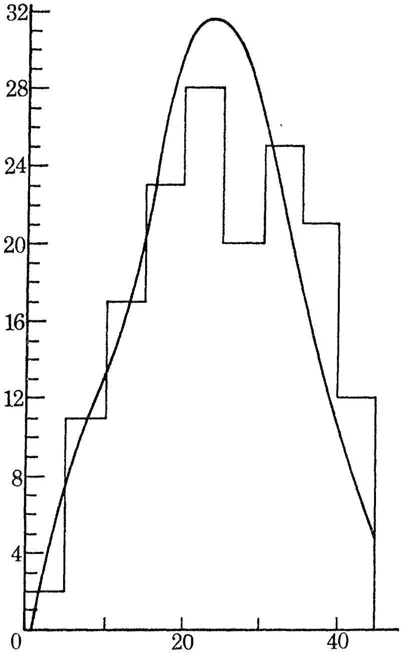


FIGURE 3

FIGURE 4

FIGURE 3. Angular distribution of events in the spectrographs up to 45°. □, Top-side coincidences (miss magnet); ▨, top-side coincidences (through magnet); ▩, side–side coincidences (through magnet). Line 1 is the prediction for all events. Line 2 is the prediction for events passing through the magnet. Line 3 is the prediction for side–side coincidences only.

FIGURE 4. Angular distribution of events in telescopes 1 and 2, telescopes 3, 4 and 5 (o.s.t. > 1 tray) and spectrographs up to 45°.

It was shown by Menon *et al.* (1967*a*) that the variation of vertical intensity of muons with depth underground is of the form

$$I(0,h) = a\exp(-h/\lambda) \qquad (1)$$

for depths greater than $4000\,\mathrm{hg\,cm^{-2}}$. Then at a depth h below a flat surface the angular distribution with respect to spatial zenith angle, θ, is expected to be

$$I(\theta,h) = I(0,h)\sec\theta\exp\{-m(\sec\theta-1)\}, \qquad (2)$$

where $m = h/\lambda$ and the factor $\sec\theta$ comes from the expected distribution of high energy muons at the surface assuming that they are produced in the decay of pions or kaons in the atmosphere.

The angular distribution of incident muons was assumed to be of the form (2), and, by folding this into the aperture of each of the detectors, the expected distributions in the detectors with respect to projected zenith angle were calculated for various values of m. For each value of m, $I(0,h)$ was adjusted to give the total observed number of muons with ϕ less than 45°. A best fit was obtained for $m = 9$ with an uncertainty of ± 1. In table 1 the effective apertures are given for $m = 9$. The corresponding vertical intensity is $1.10 \times 10^{-6}\,\mathrm{m^{-2}\,s^{-1}\,sr^{-1}}$.

The predicted numbers of events per five degree interval of projected zenith angle, obtained using these values of m and $I(0,h)$, are shown by the curves in figures 1 to 4. In figure 4 the area under the curve has been normalized to the observed number of events. In telescopes 1 and 2 there are rather more events observed than the mean and in the spectrographs there are correspondingly less. This is reflected in the individual values of the vertical intensity given in table 1. The difference between the intensities observed with the telescopes and with the spectrographs is within statistical uncertainties.

In table 1 the intensities from the o.s.t. one tray events (row 3), and from the spectrograph events in which the trajectory misses the magnet (row 6), are not in excess of the values seen in rows 1 and 4 and row 5 respectively. This suggests that very few, if any, of these events are due to electrons.

In figure 4 it can be seen that there is a deficit of events in the 25 to 30° range and a small excess between 40 and 45°. The χ^2 probability of the observed distribution is about 10 % if the true angular distribution of incident muons is of the form (2) with $m = 9$. Evidence for a deficit in the angular interval from 25 to 30° can be seen in each of the individual distributions. The implications of this for the depth-intensity curve is discussed below. The excess between 40 and 45° seems to be confined to telescopes 1 and 2. At an earlier stage of the experiment this effect was more pronounced. For instance, at the time of the report by Menon *et al.* (1967*b*) there was a peak in the distribution between 40 and 45° and possible physical explanations of this were discussed.

At present stage, all that we can say is that the angular distribution may be somewhat broader than expected on the basis of the variation of vertical intensity with depth up to this depth; further work will be needed to confirm this, and if it turns out to be the case, to explain it.

3.2. *The vertical intensity of muons*

The vertical intensity of muons shown in each column of table 1 has been obtained by dividing the total number by the effective exposure in the vertical direction; the latter having been calculated using a value of $m = 9$ which gives the best fit for the muon angular distribution. The error quoted is purely statistical.

In calculating the intensity it has been assumed that all muons with ϕ less than

45° are of atmospheric origin. In fact, a small number of neutrino-induced muons will be included among these. From the apertures of the detectors, for ϕ less than 45° and for ϕ greater than 50°, and the observed number of muons at ϕ greater than 50°, it is predicted that there should be 3 ± 1 neutrino-induced muons among the total of 165 at less than 45°. The vertical intensity must be reduced accordingly.

TABLE 1

detector	exposure 10^7 m^2 sr s	no. of events† with $\phi < 45°$	vertical intensity 10^{-6} m^{-2} s^{-1} sr^{-1}
1, telescopes 1 and 2	3.24	42 (1)	1.30 ± 0.20
2, telescopes 3 to 5 (2-side trigger)	0.06	2	—
3, telescopes 3 to 5 (o.s.t. 1 tray only)	3.13	37	1.18 ± 0.19
4, telescopes 3 to 5 (o.s.t. > 1 tray)	3.45	39 (1)	1.13 ± 0.18
5, spectrographs (through magnet)	4.15	39	0.94 ± 0.15
6, spectrographs (miss magnet)	4.33	43 (2)	1.00 ± 0.15
total of 1, 2 and 4 to 6	15.23	165 (4)	1.08 ± 0.08

† Numbers shown in parentheses are the number of events with uncertain ϕ not plotted in figures 1 to 4.

The effective aperture of each detector is sensitive to the value of m, and the uncertainty of ± 1 in m must be allowed for. The final intensity in the vertical direction is observed as $(1.1 \pm 0.2)\ 10^{-6}\,\mathrm{m^{-2}\,s^{-1}\,sr^{-1}}$ at a depth of 7000 hg cm^{-2} of Kolar rock ($\sim$ 7600 hg cm^{-2} of standard rock, for which $\langle Z^2/A \rangle = 5.5$; the approximation sign arises because the conversion needs accurate and detailed information about muon energy loss processes and this is not yet available. In the present derivation we adopt a value for the quantity b in the energy loss equation

$$-\partial E/\partial x = a + bE + c \ln E: \quad b = 3.6 \times 10^{-6}\,\mathrm{g^{-1}\,cm^2}$$

for standard rock).

By examining the intensities of muons in the different angular intervals up to an angle of 45°, it is possible to obtain vertical intensity values down to 9500 hg cm^{-2} of Kolar rock.

The data were divided into six intervals in projected zenith angle: 0 to 20, 20 to 25, 25 to 30, 30 to 35, 35 to 40 and 40 to 45°. From a knowledge of the variation of aperture with azimuth angle a mean spatial zenith angle was assigned to each angular range. The resulting intensities are plotted at the slant depths† corresponding to these angles in figure 5. It can be seen that there is an apparent dip in the depth-intensity curve around 8000 hg cm^{-2} (Kolar), this dip corresponding to the deficit of events in the 25 to 30° angular range. It is hard to see with the present

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† Thus far we have assumed that we are dealing with a flat terrain at the surface of the mine. This, however, does not correspond to the actual situation. It should be emphasized that at a great depth such as 2316 m, and at angles upto 45°, one is concerned with a fairly large area at the surface. We have therefore obtained detailed information on the surface topography, as also the uniformity of the rock overburden and we have used them to carry out the necessary detailed corrections to obtain the values shown by the points in figure 5.

data how this can be other than a statistical fluctuation. One can of course discuss possible physical processes that can lead to such a situation, for example, there may be either a sudden change in the energy loss of muons in going to higher energies or a break in the energy spectrum of muons at the surface. If the first were true a sharp increase in the slope of the depth-intensity curve would be possible, but an equally sharp decrease in slope at a slightly greater depth would be difficult. Changes in the depth-intensity curve due to changes in the spectrum of muons would tend to be more gradual than that observed because of the smearing out effect of fluctuations in the range of muons of a given energy. For the present, until an effect is established beyond the possibility of statistical fluctuation, it is not worthwhile to discuss in detail physical processes that could yield such a result.

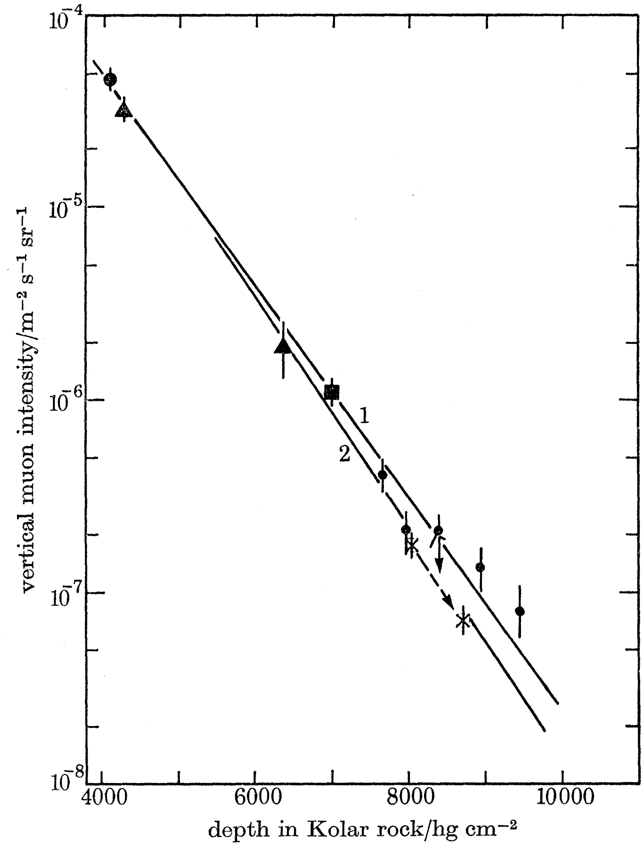

FIGURE 5. Vertical intensity of muons at depths beyond 4000 hg cm^{-2}. ●, Achar *et al.* 1965; ▲, Miyake *et al.* 1964; ✳, Meyer *et al.* 1970 (plotted at vertical depth and effective depth); ■, present data (vertical intensity at depth of observation); ●, present data (derived from inclined intensities assuming sec θ enhancement). 1, Best line through Kolar data; 2, Menon *et al.* 1967.

Between 4000 and 7000 hg cm^{-2} there are two other sets of measurements of intensity under Kolar rock, by Miyake, Narasimham & Ramana Murthy (1964) and Achar *et al.* (1965). An exponential line can be drawn through all the Kolar data beyond 4000 hg cm^{-2} and this is shown in figure 5.

Writing the depth-dependence as $I(0,h) = a\exp(-h/\lambda)$ the best fit value of λ is 790 hg cm^{-2} (Kolar). Taking the data from the present experiment alone ($h > 7000$ hg cm^{-2}) λ is a little different, being equal to h/m with $h = 7000$ and $m = 9$ as indicated in § 3.1.

A previous summary of the underground intensities has been given by Menon *et al.* (1967*a*). A best line was fitted to the data in that work; at 7000 hg cm^{-2} (Kolar) the present intensity is 26 % higher than that given there.

In relating the angular distribution to the depth-intensity curve we have assumed the normal $\sec\theta$ dependence of muon intensity on zenith angle at the surface. Keuffel *et al.* (1969) have reported that they do not observe the full $\sec\theta$ enhancement; such an effect would result in a less steep depth-intensity relation from the same observed angular distribution underground. The range of depths and of angles covered in this experiment namely, 7000 to 9500 hg cm^{-2} (Kolar), and 0 to 45°, is rather insensitive to the effect described by Keuffel *et al.* It should, however, be remarked that in another experiment carried out at Kolar (Krishnaswamy *et al.* 1969) at a depth of 3375 hg cm^{-2} (Kolar) and over a range of angles from 0 to 70°, the normally expected $\sec\theta$ enhancement has been seen. The data of Krishnaswamy *et al.* (1969), in their largest angular intervals 60 to 65° and 65 to 70°, corresponding to 7000 and 8250 hg cm^{-2} (Kolar) respectively, is in good agreement with the observations reported in this paper.

3.3. *Case–Wits–Irvine intensity measurement*

Meyer *et al.* (1970) have given a new value for the vertical intensity of muons at a depth of 8710 hg cm^{-2} local rock (8740 hg cm^{-2} of standard rock); their equipment gave no detailed information on the angular distribution of the incident muons, so it was necessary to use an angular distribution based on the assumption that the depth-intensity curve maintains its exponential form with constant slope well beyond their vertical depth. Under this assumption, with muons coming from the decay of pions and kaons only, they have derived a value of (1.84 ± 0.25) 10^{-7} m^{-2} s^{-1} sr^{-1} for the vertical intensity. This is plotted in figure 5 at the corresponding depth of 8035 hg cm^{-2} (Kolar). This intensity is only 60 % of that estimated at the corresponding depth on the basis of the best smoothed fit to the Kolar data.

The value of Meyer *et al.* does, however, agree quite well with our experimentally observed value at 7975 hg cm^{-2} but we regard this agreement as somewhat fortuitous. Most of the data on which the C.W.I. point is based are due to muons that did not arrive vertically and thus had penetrated to a greater thickness of rock than that given by the depth at which the point is plotted. Folding the expected angular distribution of muons into the aperture of the C.W.I. detector it is found that muons contribute over a range of zenith angles up to 40°, with a most probable value of about 23°. The C.W.I. data thus applies to an effective depth of about 9500 hg cm^{-2} (standard rock). In figure 5 the C.W.I. point is shown displaced to the corresponding

Kolar depth (8720 hg cm^{-2}) with the intensity appropriately changed; this has been done using their assumed angular distribution.

It is relevant to point out that in the present experiment all events have been observed with neon flash tube arrays, and with such visual detectors it is possible to distinguish clearly between various types of events. It is thus difficult to see how a value of muon intensity could be obtained that is systematically too high.

4. Energy of the observed muons

The experiment was not designed to investigate the energy of the observed muons, but a study of their electromagnetic interactions in the detectors allows a rough estimate to be made of the mean muon energy.

A study was made of 49 muons with projected zenith angles less than 50° observed in telescopes 1 and 2. Each of the muons passed through two 2.5 cm thick layers of lead absorber and was observed in the flash tube trays on both sides of each layer. Taking into account the measured projected zenith angles and estimated azimuth angles of the events, this represents 98 traversals of lead absorber of mean thickness 60 g cm^{-2}. In all, seven showers were observed with four or more electrons seen to leave the absorber in which the shower was initiated. R. Craig (unpublished thesis, Durham 1969) has calculated the probability of observing showers with four or more electrons, produced by muons of various energies in traversing 60 g cm^{-2} of lead assuming that the showers may be initiated in the lead absorber either by a knock-on electron, by an electron from pair production or by a bremsstrahlung photon. The shower curves of Crawford & Messel (1962) and Buja (1963) were used to calculate the probabilities of observing showers in the flash tube trays with greater than a given number of electrons. The results of the calculation are given in figure 6 for muons of unique energies from 90 to 1500 GeV. The observed frequency of showers is also plotted. We should emphasise that with neon flash tubes used as visual detectors it is not easy to identify independent electron tracks and to count their exact number but an attempt has been made. The observed number of seven showers with four or more electrons would have been produced if the muons had a unique energy of 250^{+230}_{-110} GeV. This energy could be equated to the mean energy of a spectrum of muons only if the probability of observing four or more electrons were proportional to the muon energy. Taking into account the actual dependence of probability on energy one finds that the corresponding mean energy is 330^{+290}_{-140} GeV. This result is consistent with the expected mean energy of atmospheric muons at 7000 hg cm^{-2} (Kolar).

5. Celestial coordinates of atmospheric muons

The celestial coordinates corresponding to the arrival directions of muons with projected zenith angle less than 45° have been calculated. In telescopes 1 and 2 and spectrographs, information relating to azimuth is limited, and the possible coordinates for each event can be shown only as an arc on the celestial sphere. The lengths of the arcs are such that the right ascension of each event is uncertain typically by three hours. In telescopes 3 to 5 both the zenith and azimuth directions are known for those events in which more than one flash tray was traversed. The events seen in one tray only were not used in this analysis as their azimuthal directions are very uncertain. In figures 7*a* and 7*b* the distributions with respect to right ascension are plotted in 3 h cells for events from the north and south celestial hemispheres respectively. For events seen in telescopes 1 and 2 and in the spectrographs, the value taken for the right ascension was the centre of the arc on the celestial sphere. Owing to the rotation of the earth there is a uniform exposure with respect to right ascension provided that the running time is uniform with respect to sidereal time. This is true to ± 3 % when the running time is divided into three hour intervals of sidereal time. It can be seen from the figures that there is no statistically significant anisotropy in arrival directions with respect to right ascension.

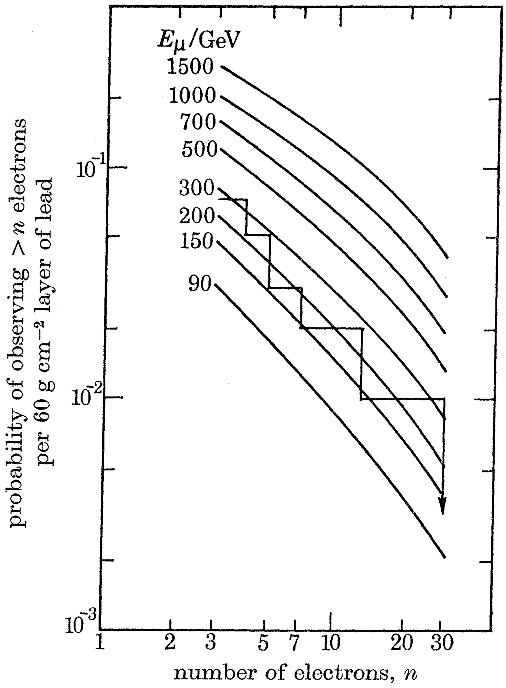

FIGURE 6. Observed probability of a shower of more than n electrons produced in the lead absorber of telescopes 1 and 2 compared with the predicted probability for muons of a given unique energy E_μ.

Since we know the declinations of the events, it is, in principle, possible to look for anisotropies in the distribution of declinations. This is complicated, however, by the variation of effective depth and aperture with zenith angles. The range of declinations covered is approximately + 55° to − 30°. One can say that the numbers of events from the north side of the zenith should be equal to the number from the south side if the flux in the region of declinations greater than +13° is the same as that at less than +13°. The observed numbers are: 100 muons from the north and 75 from the south. Again this is not significantly different from uniformity.

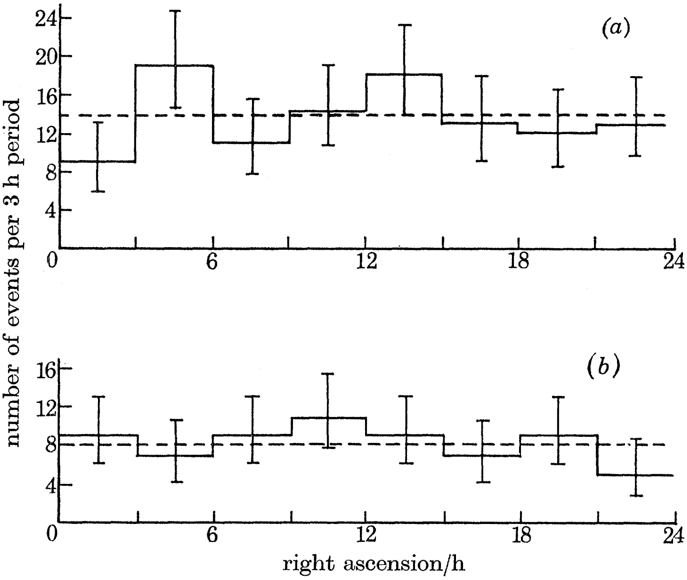

FIGURE 7. (*a*) Frequency distribution of atmospheric muons in North Celestial Hemisphere with respect to right ascension. (*b*) Frequency distribution of atmospheric muons in South Celestial Hemisphere with respect to right ascension.

6. CONCLUSIONS

The conclusions to be drawn from the experiment can be summarized as follows:

(1) The vertical intensity at 7000 hg cm^{-2} (Kolar) is $(1.1 \pm 0.2)\ 10^{-6}\,\mathrm{m^{-2}\,s^{-1}\,sr^{-1}}$ and the angular distribution follows the relation

$$I(\theta, h) = I(0, h) \sec\theta \exp\{-9(\sec\theta - 1)\}.$$

(2) The recent intensity measurements of Meyer *et al.* (1970) is only *ca.* 60 % of what we would expect.

(3) The mean energy of the atmospheric muons is not inconsistent with the expected value.

(4) There is no evidence for any celestial anisotropy; in fact an anisotropy would need to be very large for it to have been detected in the present experiment.

We are deeply indebted to the officers and other staff in the Kolar Gold Mining Undertakings for their assistance and cooperation in carrying out these experiments.

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