region, the same explanation as Moroney *et al* can be possible.

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INTERNATIONAL CONFERENCE ON COSMIC RAYS AND THE EARTH STORM Part III

III-5-8. Intensity of μ-mesons at Depths Greater than 2000 MWE

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An experiment is in progress in Kolar Gold Mines (India) to measure μ-meson intensities underground at great depths and the results obtained so far at 816, 1812, 3410 and 4280 mwe have been given. The depth intensity curve of μ-mesons is converted to the integral energy spectrum of μ-mesons at sea level and it is found that the energy spectrum can be expressed in the form $N(>E)\infty E^{-(2.9\pm0.33)}$ in the range 600 Gev $<E_\mu$ $<$2600 Gev. From this, the production spectrum of pions has been inferred and compared with the other cosmic ray data.

The energy spectrum of μ mesons at sea level, besides being of interest in itself, may throw some light on the nuclear interactions in which the parents of μ mesons are produced. The simpler method to extend the energy spectrum of μ mesons would be to measure the cosmic ray intensities at depths >2000 mwe, with large aperture cosmic ray telescopes. The depth-intensity curve of cosmic ray underground can then be converted to the integral energy spectrum of μ mesons by means of a suitable range-energy relation. With a view to extend the μ meson energy spectrum to energies much greater than 5000 Gev, we have undertaken an experiment to measure the intensity of cosmic ray μ mesons at great depths (>2000 mwe) in the Kolar Gold Mines in India. The results obtained so far will be presented here.

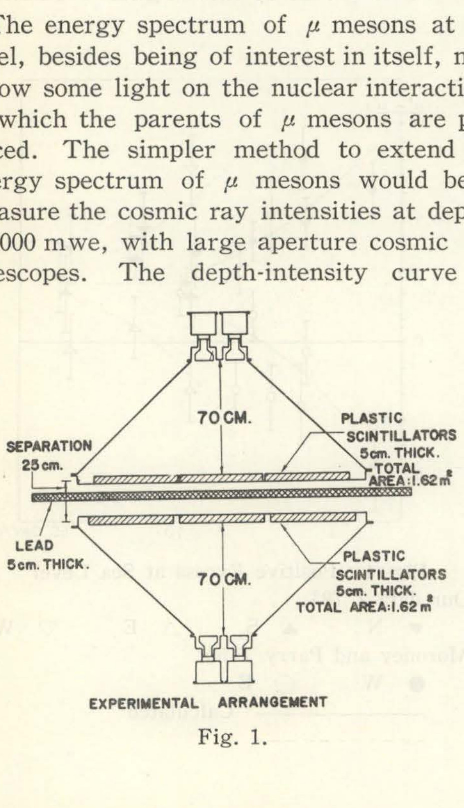

Fig. 1.

The apparatus, shown in Fig. 1, consists of two layers of plastic scintillators $156\times104\times5\ cm^3$ each, separated by 25 cm. There is a 5 cm thick lead absorber in between the two layers. Each of the layers is viewed by two 5″ diam. photomultipliers. The pulses are fed into a coincidence circuit with a resolving time 3 μ sec. With this system, we can observe cosmic ray counting rates as low as 1/day without being affected by chance coincidences due to photomultiplier noise and background radio activity. The counting rate of our telescope at the surface of the mines

(870 m a. s. l.) was 5.14×10^5 counts/hr.

In the Table, we have given the depths at which we measured the cosmic ray intensities, the counting rates and the intensity of cosmic rays at various depths. The exponents in the angular distribution of cosmic rays at various depths used by us in deriving the intensities from the observed counting rates are listed in column 4. The depths 816 mwe and 1812 mwe in our experiment are quite close to the depths 850 mwe and 1574 mwe at which the exponents in the angular distributions were measured by Randall and Hazen[4] and by Barrett[3] *et al.* respectively. We have used the exponents obtained by them at the first two depths. There is no information on the angular distribution at the other two depths, viz at 3410 mwe and 4280 mwe. Since the difference in the logarithmic derivative of depth-intensity curve and the exponent in the angular distribution ($m-n$, in the notation of reference 3) remains almost constant at depths > 1500 mwe we have deduced the exponent in the angular distribution at the other two depths from the observed depth-intensity curve by a process of interaction. An error of ±0.3 which is reasonable in the exponent of angular distribution, leads to an error 6% in the effective aperture of the

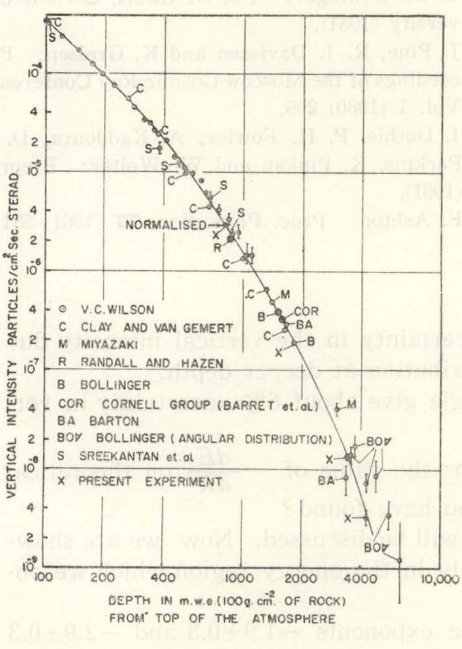

Fig. 2.

telescope and consequently in the flux values. In the last column of the table, the minimum energy a μ meson should have at sea level to reach the corresponding depth is given using the range-energy relation given by Barrett[3] *et al.* The energy loss formula is

$$\frac{dE}{dh}=1.88+.0766\ 1n\frac{E_m}{\mu c^2}+3.5\times10^{-6}E$$
$$\text{Mev/g. cm}^{-2}$$

where E is the energy (in Mev) of the μ meson, E_m is the maximum transferable energy.

In Fig. 2, we have shown the cosmic ray intensities observed by us at various depths; in addition, we have reproduced the intensities observed by various other workers as summarised in the reference 3. We have also shown the intensities observed in the same mines by Sreekantan[5,6] *et al.* from our laboratory and by Barton[7] (normalising the counting rate of his telescope at 1650 mwe with the present curve) and the intensities derived from Bollinger's[8] angular distribution experiment at 1500 mwe and at 1840 mwe as reported by Pine[9] *et al.* The errors shown in our points refer to the statical errors. It can be seen from the figure that the flux value obtained by Barton at 3350 mwe almost agrees with the present curve within the errors of his measurement. On the other hand, the flux obtained by Miyazaki at 3000 mwe seems to be higher by a factor 1.7 compared to the present curve. The flux values dirived from Bollinger's angular distribution data appear to be considerably (by a factor > 2) larger than the ones observed by us at depths 4000 mwe, if no correction is made for decay effects in the atmosphere at large zenith angles.

We have converted the depth scale in Fig. 2 into energy scale of μ mesons and presented the integral energy spectrum of μ mesons at sea level in Fig. 3. (the surface of the ground is 870 m.a.s.l.; but it is not serious at these extremely high energies.) The errors shown along the Y-axis are statistical errors; the errors shown along the X-axis, arising due to the uncertainty in the energy proportional term in the energy loss formula, may be treated as systematic errors. In the same figure, we have shown the intensities obtained by Pine[1] *et al.* and by Ashton[2] *et al.*

(magnet spectrometer results), the intensities of μ mesons derived by Duthie[10] *et al.* from their observations on γ-ray spectra at balloon altitudes and points derived from Bollinger's[8,9] observations on angular distribution of cosmic rays at 1500 mwe and 1800 mwe.

From Fig. 3, it can be seen that the intensities observed in magnet spectrometer experiments agree with our results within the errors on their measurements. This agreement shows, as was pointed out by Ashton[11], that the formula of energy loss of μ mesons takes into account all the possible energy losses upto energies 1000 Gev. Our data is entirely consistent with an integral energy spectrum of μ mesons having a constant exponent of -2.75 in the energy range 200 Gev$<E_\mu<$2600 Gev. However, if we consider the higher energy region 600 Gev$<E_\mu<$2600 Gev, the exponent can be given as -2.9 ± 0.15. In addition to the statistical error give, there is a systematic

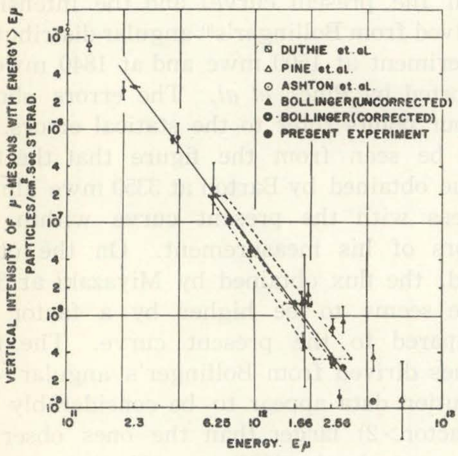

Fig. 3.

error in the exponent of ±0.3 arising from the uncertainty in the range-energy relation. If the parents of the μ mesons we observed are all pions, then the integral energy spectrum of pions at production can be given as $E^{-1.9\pm0.33}$ in the energy range 800 Gev$<E<$3500 Gev. The exponent of pion spectrum, -2.0, given by Pine[9] *et al.* in the energy range 10^{12} ev to 10^{13} ev, the exponent of the γ-ray energy spectrum, -2.0 ± 0.5, observed at balloon altitudes by Duthie[10] *et al.* in the γ-ray energy region 500 to 1500 Gev and the exponent derived from the present experiment are all consistent within themselves.

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Discussion

Yamaguchi, Y.: I would like to know the uncertainty in the vertical intensity due to the uncertainty of the azimuthal angular distribution at deeper depth.

Miyake, S.: 10% uncertainty of azimuthal angle give about 6% uncertainty in vertical intensity at middle point.

Stoker, P. H.: Have you made calculations for the value of $-\dfrac{dE}{dR}$ on theoretical grounds to compare with the empirical value you have found?

Miyake : No, after going to more deep place it will be discussed. Now we are showing the empirical formula which is applicable only in the energy region which we observed.

Greisen, K.: 1) Please tell what spectra the exponents -1.9 ± 0.3 and -2.9 ± 0.3 what refer to. 2) Please show the last slide again and explain which points come from sources.

Miyake: $E^{-1.9\pm0.3}$ is the estimated integral π-meson production spectrum. $E^{-2.9\pm0.3}$ is the μ-meson integral Energy spectrum using observed depth intensity relation and depth-relation in ref. 3.

Explained again.

Nishimura, J.: You mentioned production spectrum of π-mesons should be $E^{-1.9\pm0.2}$ at the energy region 800 BeV and 3,500 BeV. However the Bristol spectrum shows $E^{-2.8\pm0.2}$ or $E^{-2.3\pm0.2}$ corresponding the energy higher or lower than 10^{12} eV. So there should be inconsistencies between two results, and how can you determine the energy loss comparing these two data.

Miyake: We obtained the results about π-meson production spectrum $E^{-1.9\pm0.3}$ from the depth intensity relation by us and energy loss equation written in ref. 3, that shows $E^{-2.9\pm0.3}$ about μ-meson spectrum, the range observed was correspond to 800–3,500 Bev. in π-meson energy.

And we also compared to the spectrum written in the paper of Bristol group who calculate μ-meson intensity spectrum from the high energy γ-ray observation and we found in the error of energy proportional term in depth energy relation almost agree in above energy region.