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INTERNATIONAL CONFERENCE ON COSMIC RAYS AND THE EARTH STORM Part III

III-5-11. On the Energy Loss of the μ-mesons in the Ground

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One of the best methods to investigate the property of the μ-mesons is to determine the rate of their energy loss in matter and compare it with that expected from the know interactions between μ-mesons and matter. Since this valve, however, is hard to be measured directly in such high-energy region as the cosmic-ray particles have, one has to reduce it experimentally from the following two data,

D-I relation, showing the intensities of cosmic-rays as a function of depths underground energy spectrum of μ-mesons at sea level.

From these two relations the pairs of points which have same intensity of the cosmic-rays are plotted on the figure whose coordinates are the energy of the μ-mesons and the depth of the observations.

On the energy spectrum of the μ-mesons at sea level there are several experiments but only one of these measurements,[1] done at Durham, extended it's maximum energy up to 10^{12} ev. This spectrum is very good agreement with other two measurements[2,3] up to about 10^{11} ev which is the highest energy of the latter two spectra. For the D-I relation more than ten measurements have been achieved and the observing place reached down to several thousands meter water equivalent in some cases done by Bollinger,[4] Barton,[5] the group[6] of Tata Institute and so on. Since Bollinger has measured the intensities of the cosmic-rays underground as a function of arrival zenith angle at given depthes, the correction must be done to use his data as the vertical intensities of cosmic-rays at the depth equal to the length in the ground at inclined angle. This correction is due to the variation of the decay probability of the parents of the μ-mesons with the zenith angles. In this work all of the parents are assumed as the π-mesons. This assumption might not be true but even if all of these particles are assumed as the K-mesons, this correction factor increases only ten percents at the largest case. The results are plotted in Fig. 1. In this Conference new result has been reported by the group of Tata Institute. This result, as shown in Fig. 1, is in agree-

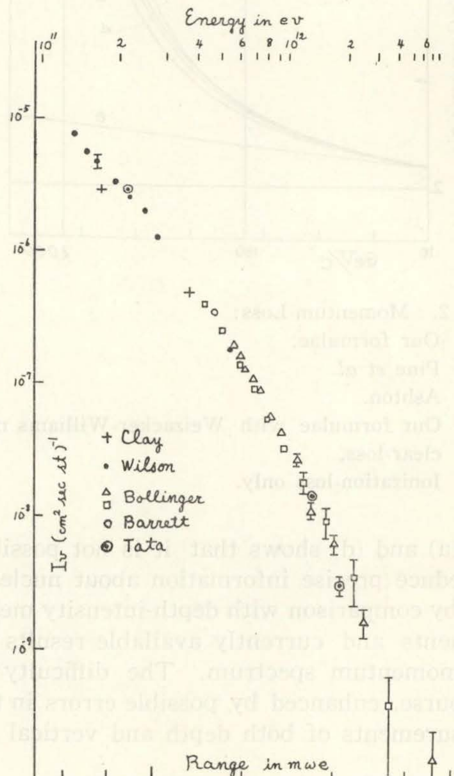

Fig. 1.

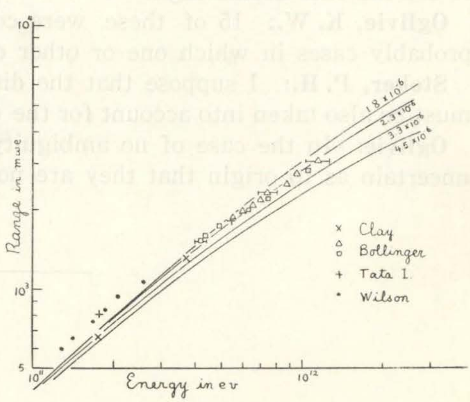

Fig. 2.

ment with the Bollinger's one. By using the energy spectrum of Durham and the D-I relation in Fig. 1, the range-energy relation in the ground has been reduced, shown in Fig. 2.

The theoretical expression of the range-energy relation has been calculated with the conventional formula for the energy loss due to the processes of ionization, bremsstrahlung, direct pair production, π-meson production and so on.

$$\frac{dE}{dx}=a+bE+k\ln\frac{E_m'}{\mu c^2}$$
$$a=1.88\times10^6\,\text{ev/g cm}^{-2}$$
$$b=1.8\times10^{-6}+C\,\text{ev/g cm}^{-2}$$
$$k=0.0766\times10^6\,\text{ev/g cm}^{-2}$$

where C expresses nuclear energy loss. The numerical value of "a" and "k" is same as that in the article published by Barrett[7] *et al* but the value of "b" is about 50 percents less than that of latter. In the energy region higher than several times 10^{11} ev the screening effect plays an important role for the processes of bremsstrahlung and direct pair production. By taking this into account, 1.05×10^{-6} has been evaluated as the value of "b" for the bremsstrahlung and 0.75×10^{-6} for direct pair production in the case of the ground. Since the nuclear interaction of the μ-mesons is not clear, this process has been interpreted as that between the nucleons and the γ-rays associated with the μ-mesons, following the semi-classical procedure of Weiszacker and Williams. In this case the energy loss is expressed to be proportional to the energy of the μ-mesons in the same way as the radiation processes and the coefficient depends linearly on the photo-nuclear cross section. If the cross section is assumed as 2×10^{-28} cm^2/nucleon, the coefficient is 0.5×10^{-6} cm^2/g. The computed range-energy relation is also shown in Fig. 2. The number attached to each curve is the values of "b" adopted.

In the low energy region, the experimental points in Fig. 2 are apparently in disagreement with the theoretical curve. But on the results given by Wilson the intensities of cosmic-rays underground have not been measured absolutely and the plots shown in Fig. 1 have been normalized by Pine[2] at certain depth. Therefore the each position of this data does not mean so much but the inclination of the line on which the points are located is important, which turned out to be parallel to the curve as expected. Thus this result does not mean to show the discrepancy between the experimental and the theoretical result. The data given by Tata group shows a small discrepancy with the curve, since these points are spreaded over the wide range to be hard to fit all of these points with the curve at one time. In the energy region higher than a few times 10^{11} ev, the experimental data agree well with the curve calculated with "b" equal to 2.3×10^{-6} which corresponds to the photonuclear cross section of 2×10^{-28} cm^2/nucleon. This value is consistent with that observed at low energy region where the more direct methods are available for studying this fact. Thus it may be concluded that from these data, so far obtained, one cannot find the evidence to show any difference on the nature of the μ-mesons at the energy region of $10^{11}\sim10^{12}$ ev compared with that at lower energy.

Once we know the range-energy relation in earth and if we assume, this relation may not change in the energy up to 10^{13} ev, the D-I relation can be converted to the energy spectrum of the μ-mesons. The energy scale thus obtained is shown at the upper edge of Fig. 1. Assuming that all of the μ-mesons at sea level are the decay product of the π-mesons at the atmosphere, the production spectrum of the π-mesons has been evaluated. The exponent of this spectrum changes from 1.65 to 2.1 with the energy of the π-mesons from 10^{10} ev to a few times 10^{12} ev and there are not any sudden change on the slope of the spectrum in this energy range.

References

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Discussion

Greisen, K.: I wish to describe Bollinger's Monte Carlo calculations since they are rather important to the present discussion. He used a mechanical computer to play the kind of game of chance described by Drs. Messel and Ogiline. At each value of meson energy, he followed the history of about 100 mesons, letting them lose energy by chance according to the theoretical formulae, until reaching the end of their ranges. The range distribution for mesons of a fixed high energy was found to be very wide. Then he assumed some incident spectrum and computed the number of mesons that would arrive at various depths underground. Within statistical fluctuation inherent in this method, the numbers were the same as would be computed by ignoring the fluctuations in the energy loss. This result is accident and depends on calculation of several factors. However, I want to emphasize that the conclusion is weak statistically-just as weak as the data now being compared on the assumption that Bollinger's conclusion is correct. It is quite important at this stage to repeat those Monte Carlo calculations with modern electronic methods that can permit much better statistical accuracy.

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III-5-12. Very Large Burst due to High Energy Muons

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It is very interesting to study electromagnetic interactions of muons with extremely high energies of order >1000 Bev because the question of whether or not the interaction would be affected by structure in the muon or nucleon will be answered. This question can at present only be studied in the cosmic radiation.

The large muon detectors at 20 mwe underground observing air showers[1] at Institute for Nuclear Study of Tokyo University was similarly used for this purpose. The experimental arrangement consist of four scintillation detectors each with an effective area of 2 m^2 and two neon hodoscope trays having its two layers which are placed under one half of the scintillation detectors (see Fig. 1). The detectors have a total area of 8 m^2 so that they can give an observation of very large number of bursts during a rather short time. About 11,000 bursts with sizes more than 100 ionizing particles initiated in rock were observed at 2,958.7 hours. The burst size S was given in terms of a sum of pulse heights in the 4 scintillation detectors that corresponds to numbers of ionizing particles only when the particles enter at vertical direction. Even bursts produced by very oblique incidence muon can trigger the detectors, so that their bursts give very larger false sizes than those caused by the same number of ionizing particles entered at vertical direction because of prolonging track length of passing particles in the scintillators. Thus it should be considered that burst sizes in this experiment do not correspond closely with transferred energies one by one.

A plot of the data, the differential frequential distribution of bursts as a function of size S from S=100 to 16,000 particles appears