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III-5-21. Review of Studies on the Momentum Spectrum of Muons

A. W. WOLFENDALE
Durham College, Durham, England

I shall summarize recent work on cosmic-ray muons, in particular measurements on muon spectra and polarization, and discuss their implications.

The relevance of spectrum measurements can be seen from the diagram. The muon spectrum occupies a key place in the sequence of diagram processes which involve both short-range and electromagnetic interactions.

Sea Level Spectrum:

Many experiments have been carried out in recent years and the upper limit of momentum measurement has been progressively extended and the statistical accuracy improved. The most recent measuements are those of the Durham group (Brooke *et al*, reported in these Proceedings) in which some 2.5×10^5

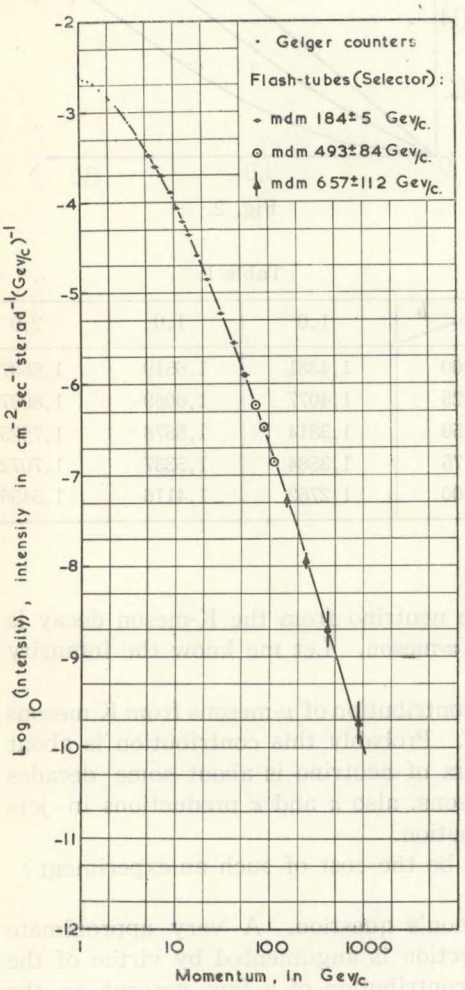

Fig. 1. The differential momentum spectrum of cosmic ray muons near sea level in the verti cal direction as measured with the Durham spectrograph (Brooke *et al*, reported in these Proceedings).

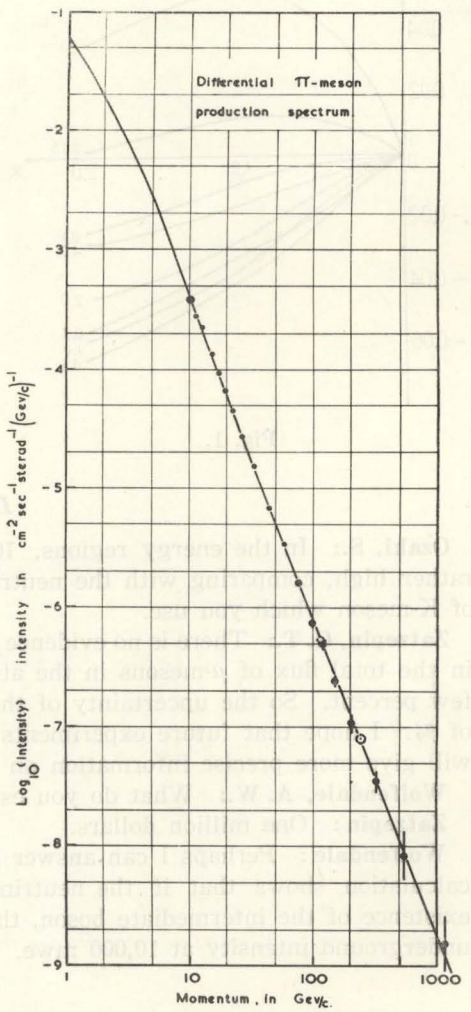

Fig. 2. The differential momentum of pions at production (Brooke *et al*).

particles were recorded and the spectrum measured to about 1,000 Gev/c. This spectrum is shown in Fig. 1. The results agree well with those found by the Cornell group up to their upper limit of just over 100 Gev/c.

Pion Production Spectrum:

An important derivation is the pion production spectrum. Assuming that all the muons come from pions, the resulting spectrum is as shown in Fig. 2. The exponent (differential) is 2.64 ± 0.05 in the range 5–1000 Gev/c. Below 5 Gev/c there is a progressive reduction in the exponent (eg. 2.07 ± 0.1 at 2 Gev/c).

Comparison with Emulsion Data on γ-Ray Cascades:

The exponent of the integral pion production spectrum is 1.64 ± 0.05 and this is a little lower than the values found by the Bristol and the Japanese groups. However, the difference cannot be regarded as significant. This can be appreciated from Fig. 3, which compares the measured integral muon spectrum with one estimated from the Bristol data, assuming, again, that pions are the only source of muons. The Bristol group (Duthie *et al*, reported in these Proceedings) have shown that the integral muon spectrum would be some ten times higher if all γ-rays and muons were derived from K-mesons. The conservative conclusion is that the K to π ratio is $\lesssim 0.4$ for energies up to 1000 Gev.

Polarization Studies:

A similar result comes from studies of the polarization of muons at sea level and underground. The polarization depends on both the nature of the parent of the muon (K or π) and the slope of the production spectrum. Papers have been given by Dr. Clark (MIT) and Dr. Asatiani (Armenia) describing counter experiments designed to determine the polarization as a function of energy.

Briefly, although the earlier high values of polarization have not been confirmed, the Russian workers still find rather high values, in the region of 0.27. The MIT work is the most precise (statistically) and they find P essentially constant at 0.21 ($\pm \sim 0.03$) from 0.2

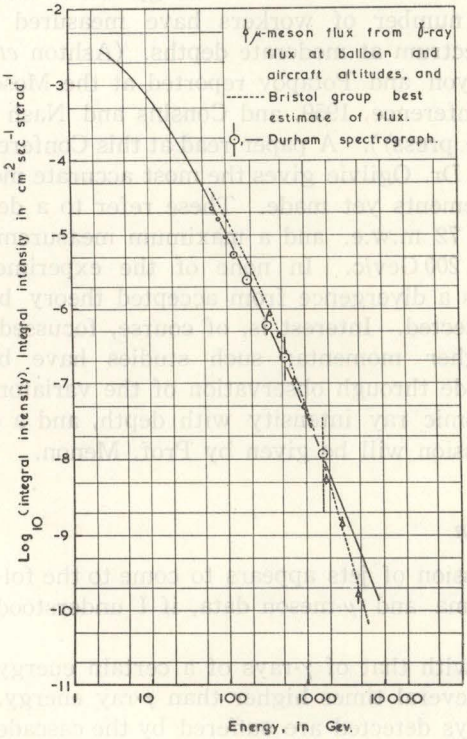

Fig. 3. Comparison of the integral muon spectrum at sea level with that derived from the γ-ray measurements (Duthie et al, reported in these Proceedings).

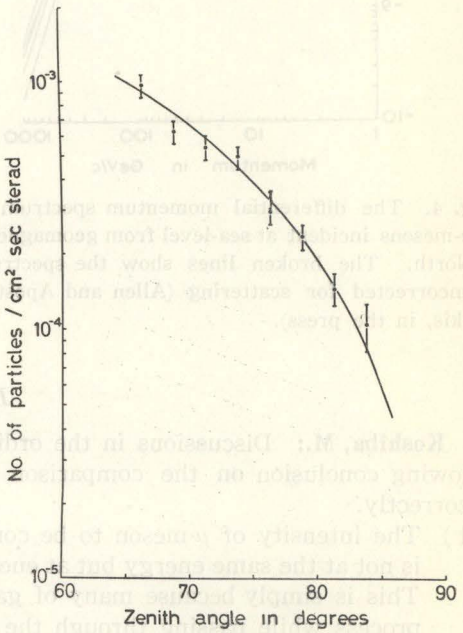

Fig. 5. The variation with zenith angle of the integral rate of cosmic rays at sea-level (Allen and Apostolakis, in the press).

to 8 Gev/c muon momentum. The conclusion appears to be that there in no evidence for any appreciable increase in the K/π ratio for pion energies up to about 16 Gev and that ratio is $\lesssim 0.3$.

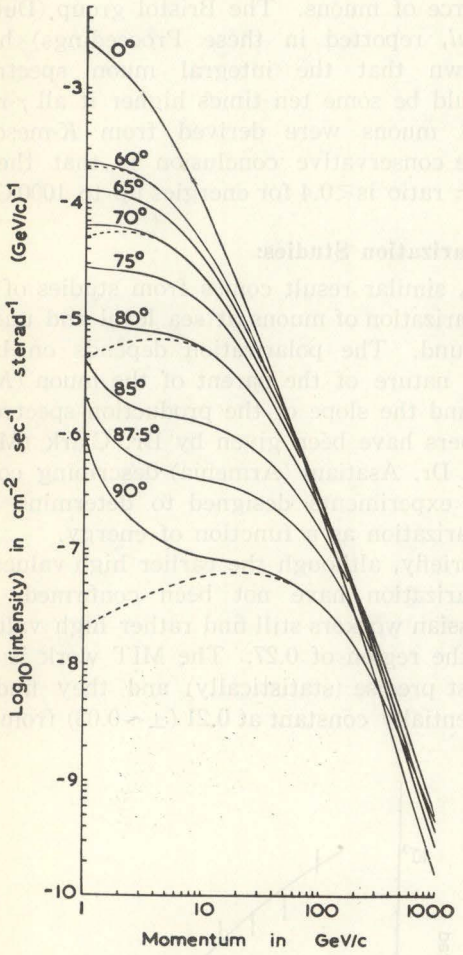

Fig. 4. The differential momentum spectrum of μ-mesons incident at sea-level from geomagnetic North. The broken lines show the spectrum uncorrected for scattering (Allen and Apostolakis, in the press).

Incline Muon Spectrum:

Measurements on inclined spectra give some information on the K/π ratio but are more particularly useful in confirming our ideas about the propagation of the components in the atmosphere. Accurate calculations have been made by Allen and Apostolakis (in the press) and are shown in Fig. 4. Some preliminary measurements have been reported by Prof. Sekido's group and by the Durham group (Ashton and Wolfendale, reported in these Proceedings) both using solid iron magnets. Both experiments give results consistent with expectation.

The emulsion group at Durham (Allen and Apostolakis) also get good agreement with expectation assuming that pions are the main source of muons (Fig. 5).

Underground Spectra:

The main interest here is in the determination of the rate of energy loss of muons. A number of workers have measured the spectrum at moderate depths. (Ashton *et al*, Dayon and Potapov reported at the Moscow Conference, 1959, and Consins and Nash (in the press)). A paper read at this Conference by Dr. Ogilvie gives the most accurate measurements yet made. These refer to a depth of 72 m.w.e. and a maximum measurement of 200 Gev/c. In none of the experiments has a divergence from accepted theory been detected. Interest is, of course, focussed on higher momenta; such studies have been made through observation of the variaton of cosmic ray intensity with depth, and a discussion will be given by Prof. Menon.

Discussion

Koshiba, M.: Discussions in the ordinary session of jets appears to come to the following conclusion on the comparison of gamma and μ-meson data, if I understood correctly.

1) The intensity of μ-meson to be compared with that of γ-rays of a certain energy is not at the same energy but at energy of several times higher than γ-ray energy. This is simply because many of gamma rays detected are suffered by the cascade process while passing through the atmosphere.
2) Considering the above effect and poor statistics the comparison can be made up to only the energy region $E_\gamma \sim 10^{12}$ ev, which compounds $E_\mu \sim 3.10^2$.
3) In a comparison of the absolute intensities, one has to take into account possible

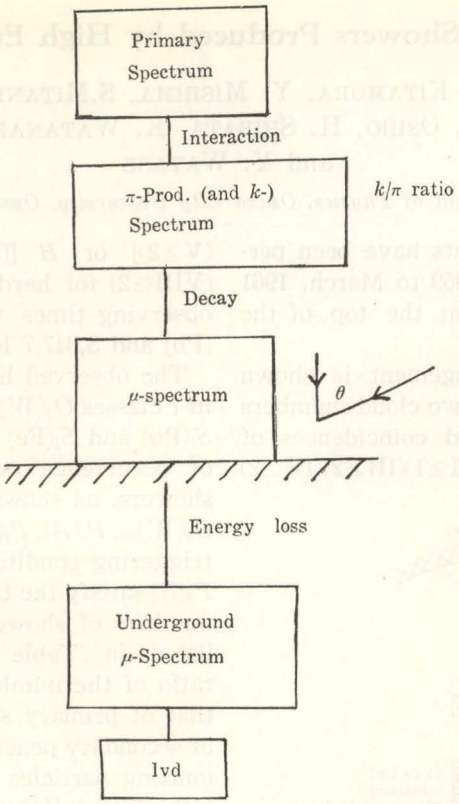

Fig 1.

errors, which might come from the absolute calibration of energy and the evaluation of detection efficiency.

4) The data on spectrum of γ-rays below and around 10^{12} ev obtained by various laboratories, now appear to come to a good agreement, $E^{-2.0\sim-2.3}$. Beyond that energy, there seems to remain some discrepancies between data in γ-ray measurement carried out by various laboratories, where only poor information is available from the μ-meson spectrum. We hope, μ-meson people have better statics in this energy region in near future.