# SPECTRUM OF HIGH-ENERGY COSMIC-RAY MUONS AT A ZENITH ANGLE OF 75°*

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The energy spectrum of high-energy cosmic-ray muons was measured at an angle of 75° from the vertical. The results show that the direct muon production inferred from underground measurements of muons with energies over 1000 GeV is not observed in these spectrograph measurements at energies up to 300 GeV.

Bergeson et al.[1] have shown that the results of their recent measurements of the very high-energy muon flux at different zenith angles are not in accord with the usual hypothesis that these muons are derived from the decay of high-energy mesons produced in the interaction of the primary cosmic rays, but their measurements require that an appreciable proportion of the highest energy muons be produced directly in the interaction of the primary nucleons with the nuclei in the atmosphere, or that these muons result from the decay of some short-lived particle which has not otherwise been detected. They find that this anomaly in the flux extends to muons with the lowest energies that they can measure in their underground experiment, muons with a mean energy near 1000 GeV. This Letter describes a measurement of the muon flux to energies of about 300 GeV at a zenith angle of 75°. These measurements, made using a magnetic spectograph with a maximum detectable momentum in excess of 300 GeV/$c$, together with other measurements[2] of the flux in the vertical direction, suggest that there is no strong anomaly in the variation of muon flux with zenith angle at muon energies of 300 GeV or less.

A schematic elevation view of the instrument used in our studies is shown in Fig. 1. The beam is defined by four scintillation counters $C1$-$C4$ and anticoincidence counters around the magnet entry and exit apertures which exclude the particles traversing the structural parts of the magnet. The magnet pole pieces are 1.8 m long and 0.5 m wide; the gap is 46 cm. The magnet was operated such that the field integral was 16.4 kG m. The helium-filled spark chambers are 1.0 m long with plate dimensions of 1.0 m by 1.5 m. The axis of the spectrometer was set at an angle of 75° from the zenith; the half width at half-maximum of the angular acceptance is 5.5°.

The momentum of the particles was determined by measuring the angular deflection of the particles by measurements of the tracks in the spark chambers. Photographs of the vertical and horizontal views of the spark chambers were made and the pictures were scanned and measured automatically using a flying-spot measuring machine connected to a computer.[3] A lower limit to the value of the maximum detectable momentum of the spectograph was determined by measuring the tracks of muons which traversed the apparatus with the magnet current off. In order to reduce the effects of multiple scattering, only muons which subsequently penetrated 1.5 m of uranium were measured. The rms deflection so measured was 1.6 mrad, corresponding to a momentum of 300 GeV/$c$ with the field on. Since this is only slightly larger than the deflection of 1.0 mrad expected from a calculation of remanent field and the multiple scattering in the 0.002-in. aluminum spark-chamber plates and in the helium in the magnet aperture, the actual maximum detectable momentum might be appreciably higher than 300 GeV/$c$ when the uncertainties of these results are considered. Indeed, a calculation of the maximum detectable momen-

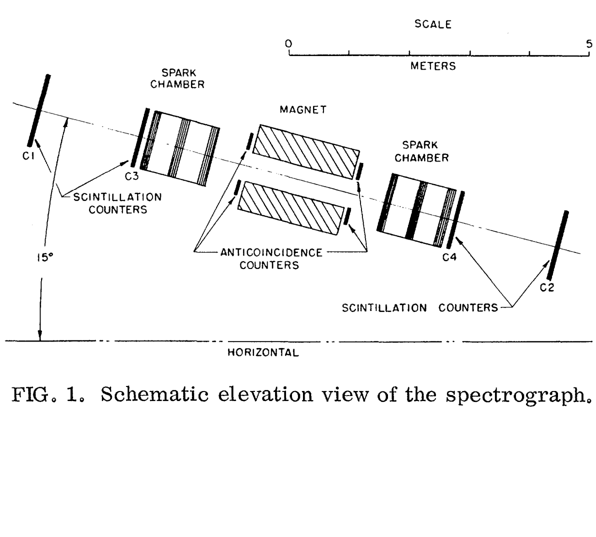


FIG. 1. Schematic elevation view of the spectrograph.

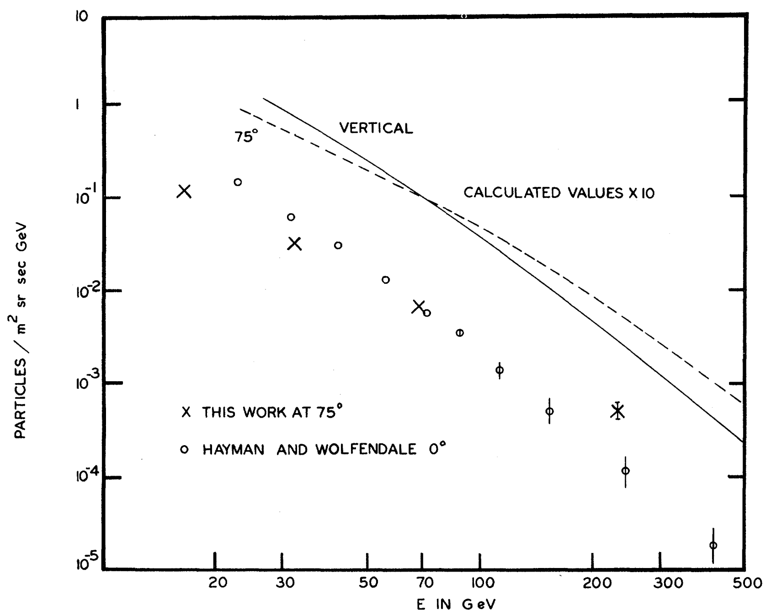


FIG. 2. Energy spectrum of very high-energy cosmic-ray muons. The curves, displaced by a factor of 10, represent the results of a theoretical calculation.

tum made from a less inclusive analysis of individual measurement errors would suggest a value of 1000 GeV/$c$, but we are not sanguine about the reliability of such methods, which implicitly ignore certain classes of errors, either in our measurements or from measurements made using other spectographs.[4]

Our measured spectrum is shown by the heavy crosses in Fig. 2 where the solid points show the results of Hayman and Wolfendale[2] in the vertical direction. In order to emphasize the variation with energy of the zenith dependence of the flux, our data have been adjusted slightly in absolute value to give the same flux as the vertical data at 60 GeV. Although our measurements extend to nominally higher energies than 300 GeV, the value we use conservatively as the maximum detectable momentum, we do not include the higher energy points on Fig. 2. In view of the steepness of the muon energy spectrum we do not feel that the values for fluxes corresponding to momenta higher than the maximum detectable momentum can be reliable in our work or the work of others.[5] It is now particularly important to adopt a conservative view concerning possible errors for spectrometer measurements at large zenith angles, as measurement uncertainties will tend to raise the observed flux assigned to large momenta and thus obscure the anomaly of interest.

The solid curve and dashed curve of Fig. 2 represent the results of a theoretical calculation of the muon flux by one of us (R.K.A.) on the basis of a particular model of nucleon-nucleon interactions and the diffusion of cosmic rays through the atmosphere. These curves are displaced by a factor of 10 so as to reduce the emphasis on the relation of the absolute values, which are model dependent, and to allow comparison of the theoretical variation of flux with angle, which is almost model independent, with the experimentally observed variation. For definiteness, the model, as used here, assumes that all of the muons result from pion decay. This similarity between the theoretical and experimental results shows that there is no important discrepancy between the observations of the muon flux at energies near 300 GeV and conventional theories of the origin of this flux.

We want to emphasize that this result is in no sense a contraindication to the data and conclusions of Bergeson et al.,[1] concerning the origin of muon fluxes at energies over 1000 GeV,[6] but might suggest that a threshold exists for the anomalous process.

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[1]H. E. Bergeson, J. W. Keuffel, M. O. Larson, E. R. Martin, and G. W. Mason, Phys. Rev. Letters 19, 1487 (1967).

[2]P. J. Hayman and A. W. Wolfendale, Proc. Phys. Soc. (London) 80, 710 (1962).

[3]T. Carides, J. G. Cottingham, A. V. Feltman, A. S. Grossman, L. B. Leipuner, J. G. Marinuzzi, and G. E. Schwender, Rev. Sci. Instr. 28, 1425 (1967).

[4]We note, for example, that the ingenious method used by the Durham group (Refs. 2 and 5) to discuss the errors in their measurements does not, in fact, establish their maximum detectable momentum. The very considerable accuracy of the correlations which they consider is neither sufficient nor necessary to insure the accuracy of measurements of the momentum of the muons which pass through their apparatus. That is, classes of errors exist which might be important and would not be detected by their techniques, while if certain other correlations hold, the accuracy could be much better than derived from the correlations which they inspect.

[5]Measurements by F. Ashton, Y. Kamiya, P. K. MacKeown, J. L. Osborne, J. B. M. Pattison, P. V. Ramana Murthy, and A. W. Wolfendale, Proc. Phys. Soc. (London) 87, 79 (1966), at large zenith angles appear to be in agreement with our results. However, their highest energy within their maximum detectable momentum is only about 79 GeV. Preliminary results of a more accurate measurement of the muon spectrum near the horizontal are given in P. K. MacKeown, S. S. Said, J. Wdowczyk, and A. W. Wolfendale, in Proceedings of the Ninth International Conference on Cosmic Rays, London, 1965 (The Institute of Physics and The Physical Society, London, England, 1966).

[6]The lowest energy point plotted in Ref. 1 is at 600 GeV at 40°–50°. Since this is a threshold, the point corresponds to a mean energy of about 900 GeV. The most significant data represent appreciably higher energies.

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# POMERANCHON SU(3) ASSIGNMENT AND TOTAL CROSS SECTIONS*

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The present analysis stems from the following experimental facts: (1) The total cross sections $\pi N$ and $KN$ seem to converge to different asymptotic values, the difference being of the order of 3 mb.[1] (2) The total cross sections of $\pi N$ and $\rho N$ are comparable, whereas $\varphi N$ is smaller by more than a factor of 2.[2] (3) $\sigma(\gamma p\to\varphi p)/\sigma(\gamma p\to\rho p)$ is smaller than the predicted SU(3) ratio by[3] about a factor of 15; this discrepancy comes in fact from (2) as suggested by the vector-meson dominance of the electromagnetic current. These facts can be partially explained by SU(3) breaking: For example, the quark model[4] starts from (1) and explains (2) and (3).

In this Letter the approach is different: SU(3) is assumed to be an exact symmetry for scattering amplitudes even at energies 10-20 GeV; the high-energy behavior is given by exchanges in the $t$ channel, the main contribution coming from the Pomeranchon of which we want to determine the SU(3) assignment.

We make the general assumption that the Pomeranchon is a linear superposition of a singlet and an octet state with a mixing angle $\alpha$[5]:

$$|P\rangle=|P_1\rangle\cos\alpha+|P_8\rangle\sin\alpha.$$

Consequently the contribution of $P$ exchange to the forward elastic meson-nucleon scattering amplitudes is

$$A_p^{\pi}=(\cos\alpha+2^{-1/2}\sin\alpha)A_p^{(0)},$$

$$A_p^{K}=[\cos\alpha-(2\sqrt{2})^{-1}\sin\alpha]A_p^{(0)},$$

$$A_p^{\rho}=A_p^{\omega}=(\cos\alpha+2^{-1/2}\sin\alpha)A_p^{(1)},$$

$$A_p^{\varphi}=(\cos\alpha-\sqrt{2}\sin\alpha)A_p^{(1)},$$

where (0), (1) stands for $0^-$, $1^-$ octets.

If we assume universality for the meson-meson-$\boldsymbol{P}$ coupling, we can derive the following conclusions that may be experimentally tested:

$$\lim_{s\to\infty}\left\{\frac{\sigma_T(\pi p)}{\sigma_T(Kp)}\right\}=\frac{2\sqrt{2}+2\tan\alpha}{2\sqrt{2}-\tan\alpha},\tag{1}$$

$$\lim_{s\to\infty}\left\{\frac{\sigma_T(\pi p)}{\sigma_T(\rho p)}\right\}=1,\tag{2}$$

$$\lim_{s\to\infty}\{\sigma_T(\varphi p)\}=\lim_{s\to\infty}\{2\sigma_T(Kp)-\sigma_T(\pi p)\}.\tag{3}$$

Let us now consider a finite $s$; in addition to $P$, one can exchange the $2^+$ $I=0$ states $f$ and $f'$ (we