good account of the inelastic scattering cross sections discussed in this paper.[15]

We wish to thank C. Gruhn and P. Locard for supplying us with experimental data before publication, G. Satchler for helping us in the early stages of this work, T. T. S. Kuo for supplying us with his unpublished RPA results, and G. E. Brown for an interesting conversation. We also express thanks to R. Haybron and T. Tamura for supplying us with the DWA code used in this work.

[1]T. T. S. Kuo and G. E. Brown, Nucl. Phys. 85, 40 (1966) and, A92, 481 (1967), and A114, 241 (1968); T. T. S. Kuo, Nucl. Phys. A90, 199 (1967), and A103, 71 (1967).
[2]D. Slanina and H. McManus, Nucl. Phys. A116, 271 (1968).
[3]A. Kallio and K. Kolltveit, Nucl. Phys. 53, 87 (1964).
[4]G. E. Brown, Unified Theory of Nuclear Models and Nucleon-Nucleon Forces (North-Holland Publishing Company, Amsterdam, The Netherlands, 1967), 2nd ed.
[5]N. K. Glendenning, Phys. Rev. 144, 839 (1966); G. R. Satchler, Nucl. Phys. 55, 1 (1964), and 77, 481 (1966); V. A. Madsen, Nucl. Phys. 80, 177 (1966).
[6]K. A. Amos, V. A. Madsen, and I. E. McCarthy, Nucl. Phys. A94, 103 (1967).
[7]F. G. J. Perey and D. S. Saxon, Phys. Letters 10, 107 (1964).
[8]Jay Atkinson and V. A. Madsen, Phys. Rev. Letters 21, 295 (1968).
[9]V. Gillet and M. A. Melkanoff, Phys. Rev. 133, B1190 (1964).
[10]K. Yagi et al., Phys. Letters 10, 186 (1964); E. L. Peterson et al., Nucl. Phys. A102, 145 (1967).
[11]T. T. S. Kuo, unpublished.
[12]V. Gillet and N. Vinh Mau, Nucl. Phys. 54, 321 (1964); V. Gillet, A. Green, and E. Sanderson, Nucl. Phys. 88, 321 (1966); V. Gillet, and E. Sanderson, Nucl. Phys. 91, 292 (1967).
[13]M. P. Fricke and G. R. Satchler, Phys. Rev. 139, B567 (1965); G. R. Satchler, Nucl. Phys. A92, 273 (1967).
[14]D. Agassi and R. Schaeffer, Phys. Letters 26B, 703 (1968).
[15]F. Petrovich, D. Slanina, and H. McManus, Bull. Am. Phys. Soc. 12, 12 (1967), and Michigan State University Technical Report No. MSPT-103, 1967 (unpublished).

ORIGIN OF MUON-POOR EXTENSIVE AIR SHOWERS

R. Maze
Laboratory of Cosmic Physics, Verrières le Buisson, France

and

J. Wdowczyk
Institute of Nuclear Research, Laboratory of High Energy Physics, Lodz, Poland

and

A. W. Wolfendale
Department of Physics, University of Durham, United Kingdom

and

A. Zawadzki
Institute of Nuclear Research, Laboratory of High Energy Physics, Lodz, Poland
(Received 28 February 1969)

Consideration is given to the relative intensities of muon-poor extensive air showers observed at mountain altitudes and at sea level. It is shown that the available results to date do not support the earlier hypothesis that primary gamma rays are responsible, and instead, a process involving charged primary cosmic rays is indicated.

Observations on extensive air showers (EAS) over a number of years at Lodz, Paris,[1-3] and Chacaltaya[4-6] have shown the existence of a distinct class of air showers containing a deficit of muons. Two alternative explanations have been put forward—that the showers are due to energetic primary gamma rays ($E_\gamma \approx 10^{14}$-10^{15} eV) or that they come from the interactions of primary charged particles.

The arguments so far[2] have favored the primary-gamma-ray hypothesis but we present in this note considerations which suggest the reverse, that is, that the muon-poor showers are due to the nuclear interactions of charged primaries in the atmosphere.

The impetus for the present work was the analysis by Bergeson et al.[7] in which an attempt was made to develop a coherent cosmic-ray model based on "direct" muon production. In this work the authors are able to account for a number of phenomena, among them the existence of muon-poor EAS, the suggestion being that they result from energetic electrons which in turn come from the decay of massive particles generated in the collisions of primary cosmic rays with air nuclei. The quote the results on the absolute frequencies of showers recorded at Lodz[1-3] and Chacaltaya[4-6] and show that the latter agrees well with expectation whereas the Lodz intensity is too high by a factor approaching 10. However, the intensities plotted are those quoted by the respective authors on the assumption that the showers are induced by primary gamma rays and it is necessary to correct the energy scale if they are in fact generated in the atmosphere by primary nuclei. When a correction is applied, the Lodz intensity is displaced to lower energy whereas the Chacaltaya point is virtually unaltered (the showers recorded at Chacaltaya are at near maximum development), and the result is that both intensities are close to expectation.

In what follows a more detailed analysis of the problem is given. Calculations have been performed of the expected frequency of detection of muon-poor showers above a certain size as a function of depth in the atmosphere both for primary gamma rays and for primary nuclei under the assumption that both energy spectra have the same shape (the shape of the conventional primary cosmic-ray spectrum). Allowance has been made in the calculations for the effect of fluctuations in development and consideration has also been given to the change in the angular distribution of the showers with increasing depth. The results for the frequency of showers above a fixed size N are shown in Fig. 1, where the ratio of the predicted frequency at Lodz (near sea level) to that at Chacaltaya (550 g/cm^2 below the top of the atmosphere) is given as a function of N.

It is clear that there is a significant difference between the ratios predicted for the alternative assumptions about the primary particles and a distinction should be possible by recourse to observations at the two locations. The data reported so far[1-6] refer to different threshold sizes, but by interpolation of the Chacaltaya data the

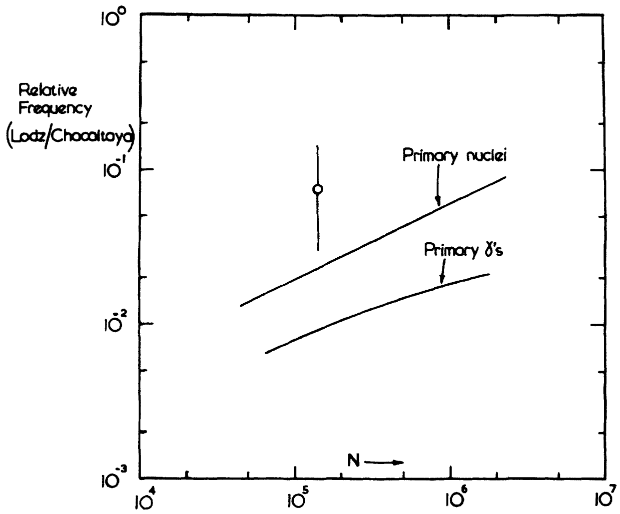

FIG. 1. Relative frequency of muon-poor EAS (Lodz/Chacaltaya) as a function of threshold shower size N.

frequency for $N = 1.4\times 10^5$ (the threshold size recorded by the Lodz array) has been determined. The Chacaltaya intensity is estimated to be about 3×10^{-12} cm^{-2} sec^{-1} sr^{-1}, and the corresponding primary energy is about 1.5×10^{14} eV if the showers are initiated either by primary γ rays or by electrons arising from nuclear interactions of primary protons in the atmosphere (in the latter case the energy quoted refers to the energy of the initiating electron). The Lodz intensity for the same threshold size is $(6_{-2}^{+3})\times 10^{-13}$ cm^{-2} sec^{-1} sr^{-1}; the corresponding primary energies are approximately 8×10^{14} eV (primary gamma rays) and 4×10^{14} eV (nuclear interactions).

In deriving the expected frequencies of detection, and their ratio, allowance has been made for the different angular distributions at the two locations. The resulting ratio is shown in Fig. 1. Although experimental shortcomings make the uncertainty in the ratio rather large, it is clear from Fig. 1 that it is inconsistent with the primaries being gamma rays. This conclusion is strengthened when it is realized that if, as would be more likely, the primary gamma spectrum had a steeper slope than that of the charged particles, then the curve for the case of primary gamma rays would be depressed. Conversely, if the showers are generated by a nuclear process, the cross section of which is rising with increasing energy, the expected Lodz-Chacaltaya ratio will be higher than that drawn in Fig. 1 in better agreement with experiment.

Taking the results presented here alone, it is possible to devise a mechanism responsible for the muon-poor showers in terms of nuclear interactions with occasional large values of K_{π^0}, the fraction of energy going into π^0 mesons. However, very recent experimental results reported by some of us,[8] which show an angular distribution flatter than that of normal showers, are very difficult to explain in this way but are more easily interpreted in terms of a "Utah-type" mechanism. In this interpretation a heavy intermediate particle which has a comparatively long lifetime (of the order of 10^{-9} sec) and which has a significant branching ratio for producing a decay electron is required. With reference to the present results it is interesting to note that this mechanism would also give rise to a variation of the relative intensity with N higher than that shown for "primary nuclei" in Fig. 1 and therefore more in accordance with observation.

With such a long-lived particle the detected muon-poor showers would all be near maximum development at both locations and the ratio of frequencies would be higher than that shown for "primary nuclei" in Fig. 1, in better agreement with observation.

At this stage, however, it should be stressed that neither the precision of the experimental results nor the range of theoretical possibilities examined is great enough for us to be dogmatic in confirming a "Utah-type" mechanism.

[1]R. Firkowski, J. Gawin, A. Zawadzki, and R. Maze, in Proceedings of the International Conference on Cosmic Rays and the Earth Storm, Kyoto, 1962 (The Physical Society of Japan, Tokyo, Japan, 1962), Vol. III, p. 123.

[2]J. Gawin, J. Hibner, J. Wdowczyk, A. Zawadzki, and R. Maze, in Proceedings of the Ninth International Conference on Cosmic Rays, London, 1965, edited by A. C. Stickland (The Institute of Physics and The Physical Society, London, England, 1966), p. 639.

[3]J. Gawin, R. Maze, J. Wdowczyk, and A. Zawadzki, Can. J. Phys. 46, S75 (1968).

[4]K. Suga, I. Escobar, K. Murakami, V. Domingo, Y. Toyoda, G. Clark, and M. La Pointe, in Proceedings of the Eighth International Conference on Cosmic Rays, Jaipur, India, 1963, edited by R. Daniels et al. (Commercial Printing Press, Ltd., Bombay, India, 1964), pp. 4-9.

[5]Y. Toyoda, K. Suga, K. Murakami, H. Hasegawa, S. Shibata, V. Domingo, I. Escobar, K. Kamata, H. Bradt, G. Clark, and M. La Pointe, in Proceedings of the Ninth International Conference on Cosmic Rays, London, 1965, edited by A. C. Stickland (The Institute of Physics and The Physical Society, London, England, 1966), p. 708.

[6]K. Kamata, S. Shibata, O. Saavadra, V. Domingo, K. Suga, K. Murakami, Y. Toyoda, M. La Pointe, J. Gaebler, and I. Escobar, Can. J. Phys. 46, S72 (1968).

[7]H. E. Bergeson, J. W. Keuffel, M. O. Larson, G. W. Mason, and J. L. Osborne, Phys. Rev. Letters 21, 1089 (1968).

[8]Ph. Catz, J. Gawin, R. Maze, J. Wdowczyk, and A. Zawadzki, to be published.