Nuclear Interactions of High-Energy Cosmic Rays Observed near Sea Level*

W. PAK† AND K. GREISEN
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York

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Nuclear interactions of magnetically analyzed cosmic rays above 8 Bev in energy have been observed near sea level at two zenith angles 0° and 68° in an effort to obtain information on the muon nuclear interaction cross section for events of ~200 Mev threshold energy, and on the vertical intensity of sea-level protons having ~20 Bev median energy. The muons selected in the present experiment are comparable in energy to those at an underground depth of ~300 meters water equivalent (m.w.e.). The present result agrees well with data of Avan at 310 and 590 m.w.e. All three points, however, lie above the cross sections calculated with the Williams-Weizsäcker method. In view of large statistical errors the departure cannot be taken too seriously, but it suggests an increase of photonuclear cross section with energy. The statistical error in the derived proton intensity is also large, but there is no previous valid measurement, to our knowledge, of the sea level proton intensity at this high an energy. The average elasticity of high-energy nuclear collisions consistent with our proton intensity is roughly 50%. Our spectral point, together with results of previous experiments at about 1 Bev/c, indicates a differential proton spectrum that can be represented by a power law with exponent $\gamma=1.9\pm0.3$. The spectrum of the primary particles which contribute to the sea-level proton flux in the 1–20 Bev energy range fits a power law with $\gamma\simeq2.4$. The fact that the sea-level spectrum is harder than the primary spectrum suggests that the elasticity is an increasing function of energy.

APPARATUS

THE details of the experimental arrangement have been reported elsewhere.[1,2] Briefly, an apparatus consisting of a magnet spectrometer and a multiplate cloud chamber was used to observe cosmic rays at zenith angles 0° and 68°. The spectrometer was used to determine the charge and the momentum of the impinging particles, and the cloud chamber to observe the interactions.

A 15-cm layer of lead was placed on top of the spectrometer to eliminate the soft component present in the sea-level cosmic radiation. While this layer did not substantially affect the muon intensity, it reduced the N-component intensity by a factor of e. Nevertheless, the interaction cross section of the N component is sufficiently large that the N-component interactions in the cloud chamber still outnumbered those due to the muons. At 68° spectrometer orientation, however, the apparatus detected particles which, on the average, had traversed material equivalent to ~2.7 times the vertical atmospheric depth. Because of its relatively short absorption length, the N component at this orientation is negligible in intensity, while the high-energy muon component remains relatively unaffected. Therefore, interactions observed at 68° orientation can be attributed entirely to muons and any increase in the rate of interactions, when the spectrometer is tipped back to 0°, to the N component.

The present report is based on 3158 tracks observed at 68° and 4869 at 0°. A track represents a traversal through nine lead plates each 6.7 g/cm^2 thick. The total track lengths in which interactions could have been observed if they had occurred were 1.5×10^5 g/cm^2 at 68° and 1.8×10^5 g/cm^2 at 0°. Two interactions were observed at 68° and seven at 0°, no consistent qualitative difference being apparent in the nature of the interactions at these two angles. Though these numbers of events are small, they concern physical quantities on which previous data are almost nonexistent; hence an analysis of the frequency of the events has some significance.

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† Now at Stevens Institute of Technology, Hoboken, New Jersey.
[1] B. P. Roe, Ph.D. thesis, Cornell University, Ithaca, New York 1959 (unpublished).
[2] B. P. Roe and S. Ozaki, Phys. Rev. 116, 1022 (1959).

MUON NUCLEAR INTERACTION CROSS SECTION

It has long been known[3] that muons are capable of producing nuclear interactions through electromagnetic processes in which the virtual photons accompanying the relativistic muons are considered to interact with nuclei. Numerous papers[4] in the last decade have reported measurements of this phenomenon. In all cases separated muon beams were obtained either by going underground or by placing thick absorbers[5] above the detecting apparatus. The present technique of eliminating contaminants by sampling sea-level cosmic rays at a large zenith angle is new. Furthermore, the spectrometer made it possible to reject muons that would be energetically incapable of producing observable nuclear interactions. However, such use of a spectrometer sharply restricted the solid angle, rendering attainment of statistical accuracy difficult.

The settings were such that the aperture of the instrument was zero for particles below 8 Bev. With increasing energy the aperture opened up gradually, to 10% of full aperture at 10.5 Bev, 50% at 18 Bev, and 90% at 48 Bev. By taking into account this variation of aperture with energy, the shape of the muon spectrum at 68° zenith angle, and the energy dependence of the Williams-Weizsäcker cross section, the effective muon energy to be associated with the

[3] E. P. George and J. Evans, Proc. Phys. Soc. (London) **A63**, 1248 (1950); **A64**, 193 (1951).
[4] For a review of recent works see reference 14.
[5] I. B. McDiarmid, Phys. Rev. **109**, 1792 (1958).

observed mean cross section was computed to be 33 Bev.

The threshold secondary energy of the nuclear events observed in the cloud chamber is estimated to be about 200 Mev. In Fig. 1 our experimental cross section is compared with the results of other experiments[5–9] having similar values of threshold energy. The results of measurements in which only "penetrating shower production" was observed are not included in the plot, since such events have a threshold secondary energy above one Bev, and are sensitive in frequency to the rather uncertain value of this threshold.

In constructing Fig. 1 the knowledge of the underground muon spectrum at any given depth made possible the transformation of underground depths into equivalent muon energies. Following Barrett *et al.*,[10] the underground muon spectrum was taken to be

$$\mu(E,s)=\text{const}[E+E(s)]^{-2.64}[1+E(s)/E_0+E/E_0]^{-1},$$

where the first term in brackets represents the shape of the pion production spectrum,[11] $E_0=90$ Bev, and $E(s)$ is the energy loss suffered by muons in reaching the underground depth s.

The solid line in Fig. 1 is the expected cross section calculated on the basis of the Williams-Weizsäcker method[12,13]:

$$\sigma_\mu(E)=(\sigma_\nu\alpha/\pi)[\ln^2(E/\epsilon)-0.11\ln(E/\epsilon)]\ \text{cm}^2/\text{nucleon},$$

where σ_ν is the photonuclear cross section per nucleon, α is the fine-structure constant, and ϵ is the threshold energy. On the basis of measured values of photonuclear cross sections extending up to about 500 Mev, σ_ν was assumed to be independent of energy and taken to be 1.4×10^{-28} cm²/nucleon.[14]

In the low-energy region the experimental results show reasonable agreement with the expected cross sections. The high-energy points, however, lie consistently above the expected values. In view of the large statistical uncertainties the apparent discrepancy may be accidental. If it is real, however, it may be ascribed to the assumed constancy of the photonuclear cross section beyond 500 Mev, and may indicate a rise of σ_ν with energy.

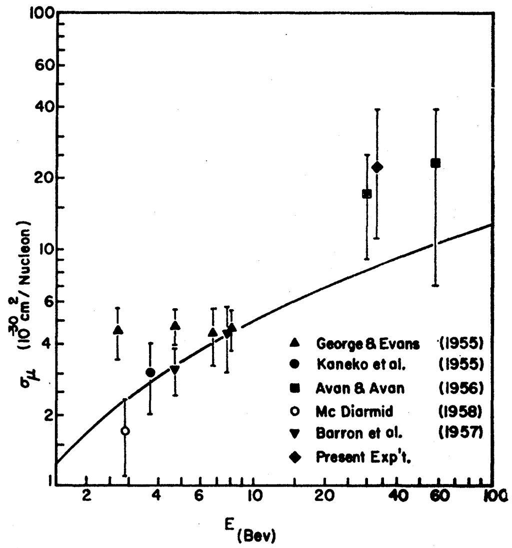

FIG. 1. Star production by muons. See references 5–9.

SEA-LEVEL PROTON INTENSITIES

With the spectrometer in the vertical orientation, in spite of the lower mean value of the muon energy, the number of interactions per incident particle was three times as great as at 68°, indicating that the

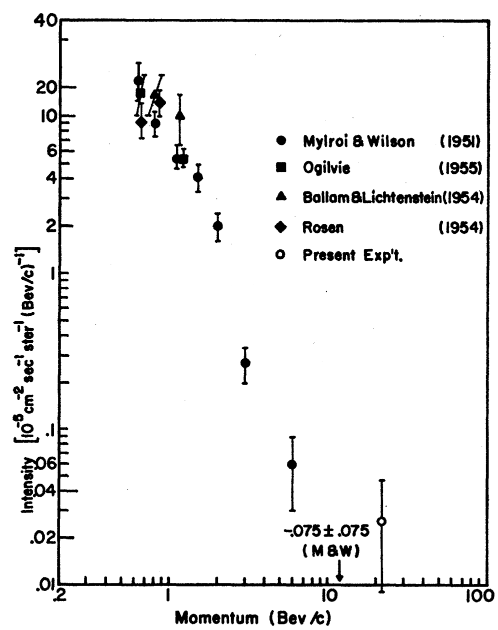

FIG. 2. Differential proton momentum spectrum at sea level. (See references 19–22.)

[6] E. P. George and J. Evans, Proc. Phys. Soc. (London) **A68**, 829 (1955).

[7] S. Kaneko, T. Kubozoe, M. Okazaki, and M. Takahata, J. Phys. Soc. Japan **10**, 60 (1955).

[8] L. Avan and M. Avan, see G. N. Fowler and A. W. Wolfendale, Nuclear Phys. **3**, 299 (1957).

[9] W. Barron, M. L. T. Kannagara, A. M. Short, and A. W. Wolfendale, reference 14, p. 158.

[10] P. H. Barrett, L. M. Bollinger, G. Cocconi, Y. Eisenberg, and K. Greisen, Revs. Modern Phys. **24**, 133 (1952).

[11] The analysis of the sea-level muon spectrum by J. Pine, R. J. Davisson, and K. Greisen, [Nuovo cimento **14**, 1181 (1959)] and by W. Pak, S. Ozaki, B. P. Roe, and K. Greisen, [Phys. Rev. **121**, 905 (1961)] showed that the pion production spectrum can be well represented by a simple power law of the form

$$F(E)dE=\text{const}E^{-2.64}dE.$$

[12] E. J. Williams, Proc. Roy. Soc. (London) **A139**, 163 (1933); Kgl. Danske. Videnskab. Selskab. Mat.-fys. medd. **13**, No. 4 (1935); C. F. von Weizsäcker, Z. Physik **88**, 612 (1934).

[13] W. Heitler, *The Quantum Theory of Radiation* (Oxford University Press, New York, 1954), 3rd. ed., pp. 414–417.

[14] G. N. Fowler and A. W. Wolfendale, *Progress in Cosmic-Ray Physics and Elementary Particles* (North-Holland Publishing Company, Amsterdam, 1957), Vol. 4, p. 179.

majority of the interactions observed in the vertical orientation were due to the charged N component rather than to muons.

Measurement of the ratio of neutral to charged particles in the N component by Greisen and Walker[15] led them to conclude that pions comprise only a small fraction of the N component. In the present experiment the charge of the parent particles could be definitely determined for only four events in the 0° spectrometer orientation. All four were found to be positively charged, suggesting that the charged N component of 22-Bev median energy observed near sea level consists mainly of protons rather than pions.

The ratio of high-energy protons to muons consistent with our measurement is

$$R=(1.6\pm1.1)\%.$$

From this value of R and the intensity of primary cosmic rays, the average elasticity of high-energy nuclear collisions can be calculated by using a simple model of nucleon diffusion, such as the model proposed by Heitler and Janossy.[16] In this calculation the total nucleon-nucleon cross section (elastic plus inelastic) was taken to be 33±4 mb, extrapolating the results of present day accelerators which were available up to about 10 Bev.[17] The average elasticity was found to be $0.5_{-0.2}^{+0.1}$, where the errors include the statistical error in R, the uncertainty in the primary spectrum, the error in the nucleon-nucleon cross section, and the uncertainty in the size of air nuclei.

Since the vertical sea-level muon spectrum is well known, R can be readily converted into a value of the differential proton intensity at an energy of about 22 Bev. No previous valid measurement of proton intensity has been made in this energy range, to our knowledge. Our point is plotted in Fig. 2 along with results of other observers.[18–22] With the exception of the experiment by Mylroi and Wilson[19] the measurements are confined in the momentum range of 0.3 to 1.5 Bev/c. In this momentum range the agreement among various observations is as good as can be expected. The Mylroi-Wilson points extend from 0.6 Bev/c to 12 Bev/c. Despite large statistical errors in the high-momentum points, the salient feature of Fig. 2 seems to be that our spectral point at 22 Bev/c cannot be brought into agreement with the high-momentum data of Mylroi and Wilson. Their results would suggest that beyond about 10 Bev/c the protons do not exist at sea level in any measurable intensity. Indeed, the Mylroi-Wilson points indicate a differential spectrum of the form, $N(p)dp=\text{const}\,p^{-2.8}dp$,[19] whereas our point at 22 Bev/c, together with low-energy data, yields a power-law spectrum with a much smaller exponent, $\gamma=1.9\pm0.3$. We seek to bridge the discrepancy by suggesting that the Mylroi-Wilson points in the high-momentum region are too low because of an energy-dependent bias inherent in their method of proton identification. For that purpose these authors relied on an assumed inability of protons to penetrate 20 cm of lead absorber. If an energetic proton underwent unclear interaction in the absorber and one or more of the secondaries managed to emerge from the absorber, the proton could not be distinguished from a muon. The Mylroi-Wilson points at 3, 6, and 12 Bev/c therefore probably represent increasingly gross underestimates of the proton intensity.

The energetic protons that reach sea level have had, on the average, about five interactions in their passage through the atmosphere. Thus, the sea-level protons in the energy range 1–20 Bev are attributed to primaries of 30–700 Bev energy at the top of the atmosphere. The differential primary spectrum in this energy range can be well approximated, according to Barrett *et al.*,[10] by a power law with exponent $\gamma=2.4$. Since we obtain $\gamma=1.9\pm0.3$ at sea level, the spectrum of the progeny seems to be harder than that of their ancestors. This would be the case if the elasticity of high-energy interactions is an increasing function of energy.

ACKNOWLEDGMENTS

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[15] K. Greisen and W. D. Walker, Phys. Rev. **90**, 915 (1953).
[16] W. Heitler and L. Janossy, Proc. Phys. Soc. (London) **A62**, 374 (1949).
[17] O. Piccioni, Rapporteur, *Proceedings of the 1958 Annual International Conference on High-Energy Physics at CERN* (CERN Scientific Information Service, Geneva, 1958), p. 74.
[18] Only representative points from previous measurements are included in this plot. For more complete review of previous observations, see W. Pak, Ph.D. thesis, Cornell University, 1960 (unpublished).
[19] M. G. Mylroi and J. G. Wilson, Proc. Phys. Soc. (London) **A64**, 464 (1951).
[20] K. W. Ogilvie, Can. J. Phys. **33**, 746 (1955).
[21] J. Ballam and P. G. Lichtenstein, Phys. Rev. **93**, 851 (1954).
[22] A. Z. Rosen, Phys. Rev. **93**, 211 (1954).