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[1]W. R. Frensley and H. Kroemer, J. Vac. Sci. Technol. 13, 810 (1976).

[2]W. A. Harrison, to be published.

[3]G. A. Baraff, J. A. Appelbaum, and D. R. Hamann, Phys. Rev. Lett. 38, 237 (1977).

[4]A. G. Milnes and D. L. Feucht, *Heterojunctions and Metal-Semiconductor Junctions* (Academic, New York, 1972); B. L. Sharma and R. K. Purohit, *Semiconductor Heterojunctions* (Pergamon, New York, 1974). These books contain extensive lists of references on heterojunctions.

[5]J. R. Chelikowsky and M. L. Cohen, Phys. Rev. B 13, 826 (1976).

[6]R. L. Anderson, Solid State Electron. 5, 341 (1962); A. R. Riben and D. L. Feucht, Solid State Electron. 9, 1055 (1966); J. P. Donnelly and A. G. Milnes, IEEE Trans. Electron. Dev. 14, 63 (1967).

[7]J. L. Shay, S. Wagner, and J. C. Phillips, Appl. Phys. Lett. 28, 31 (1976).

[8]G. W. Gobeli and F. G. Allen, Phys. Rev. 137, A245 (1965).

Determination of the Neutron-Proton Ratio in Primary Cosmic Rays[a]

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The charge ratios of muons produced by the interaction of 400-GeV protons with thick copper targets were measured and the +/− ratios were found to be much larger than similar ratios for muons in the secondary cosmic rays. The difference between these charge ratios is taken to indicate that the neutron/proton ratio in the primary cosmic rays is quite large: i.e., of the order of 25:75.

It should be possible to derive the characteristics of secondary cosmic-ray fluxes on knowing the composition of the primary flux and the details of the hadron-hadron interactions. Conversely, the composition of the primary flux might be determined through such calculations and the results of measurements of the secondary fluxes. In this spirit, a large number of calculations have been conducted in an attempt to determine the quantitative relation between the secondary cosmic-ray muon charge ratio and the primary cosmic-ray neutron-proton ratio using information derived from high-energy accelerator experiments to describe the character of the hadron shower.

Although the calculations of the relation between the muon charge ratios and the primary composition are reasonably straightforward, some questions concerning nuclear effects and the treatment of cascades remain, and different authors have reached different conclusions.[1-3] It then seemed essential to investigate the problem experimentally by observing the charge ratios of muons produced by the interaction of high-energy nucleons with a thick target simulating the interaction of the primary cosmic-ray nucleons with the thick atmosphere. We describe here such a set of measurements, conducted at Fermilab, where we determined the charge ratio of muons of various energies produced in a thick target by the interaction of 400-GeV protons.

Secondary cosmic-ray muons are derived from the decay of mesons from hadron showers. At energies such that the probability of meson decay is smaller than the interaction probability, the character of the hadron shower would not change appreciably if the atmosphere were made uniformly denser, but the probability of meson decay would be reduced by the ratio of densities: The muon intensity would be reduced but the charge ratio would be unchanged. If the real atmosphere, with a density which varies exponentially with altitude, were replaced by an atmosphere of constant density, the relative importance of primary to secondary hadron interactions would be somewhat reduced and slightly smaller charge ratios would be observed as the charge asymmetry derived from the secondary interactions must be smaller than from primary interactions, inasmuch as charge-exchange processes act to equalize initial charge (or T_3) imbalances.

Some of the measurements reported here, which serve the purpose of determining the muon charge ratios derived from the interactions of protons with a thick target, have been reported previously[4,5] in connection with other goals, and more detailed descriptions of the character of the measurements may be found in those reports. In general, measurements of the charge ratios of muons produced at different energies were made by determining the intensities of positive and negative muons produced by the interaction of 400-GeV protons with copper targets of different mean densities. For technical reasons, we used copper rather than (solid) air targets. The charge of the muons was determined by magnetic analysis; the muon energies were measured by determining their range through steel and earth absorbers. Ideally, we might have simulated the cosmic-ray nucleon energy spectrum by varying the energy and intensity of the protons from the accelerator. Instead, we held the proton energy at 400 GeV, measured the muon charge ratio at different values of muon energy, and trusted to scaling in the fragmentation region to allow the necessary interpolations and extrapolations to deduce the cosmic-ray results. Ideally, we might have made measurements with neutron beams to determine the charge ratios from incident neutrons. In practice, we deduced the charge ratio for incident neutrons from the proton measurements using assumptions based on charge independence.

For a very dense target, the intensity of muons from meson decay is so greatly suppressed that sources of muons which do not scale with "atmospheric" density cannot be neglected. The intensity of prompt muons from vector-meson decay and from other internal electromagnetic effects and the intensity of Bethe-Heitler muon pairs from π^0 γ rays will be important for a copper target but negligible in the atmosphere. We eliminate the contribution from such sources by measuring the intensity of positive and negative muons as a function of target density. The target assembly consisted of three targets which could be interchanged easily. One target consisted of a 1-m-long section of copper; a second section consisted of a 2-m-long region of 1-in.-thick sections of copper separated by 1 in. of free space; the third section was made of 1-in.-thick copper sections separated by two inches of space. The three targets then presented an effective density to the photon beam of $\frac{1}{3}$, $\frac{1}{2}$, or 1, in terms of the density of copper. The whole target assembly was backed by 5 m of steel and by a 6-m steel-filled magnet used to define the charge of the detected muons. Since the decay probability of the mesons is inversely proportional to the target density, the muon flux from meson decay varies inversely with the density while the large contributions from direct processes and from Bethe-Heitler production are unchanged. If the intensities are then plotted as a function of inverse target density, the intensity from meson decay is proportional to the slope of the straight line defined by the measurements while the intercept, at inverse density zero (or infinite density) is a measure of the various direct processes as well as certain backgrounds. The graph of Fig. 1 shows a typical measurement and illustrates the simplicity of the data analysis. Measurements were made of the muon charge ratios at effective muon energies of 53, 105, 180, and 230 GeV. The graph of Fig. 2 presents the measured ratios as a function of $x = E_\mu/E_p$ where the solid curve shows the interpolated values taken for the analysis which related these measurements to results expected from an incident proton spectrum like the primary cosmic-ray flux.

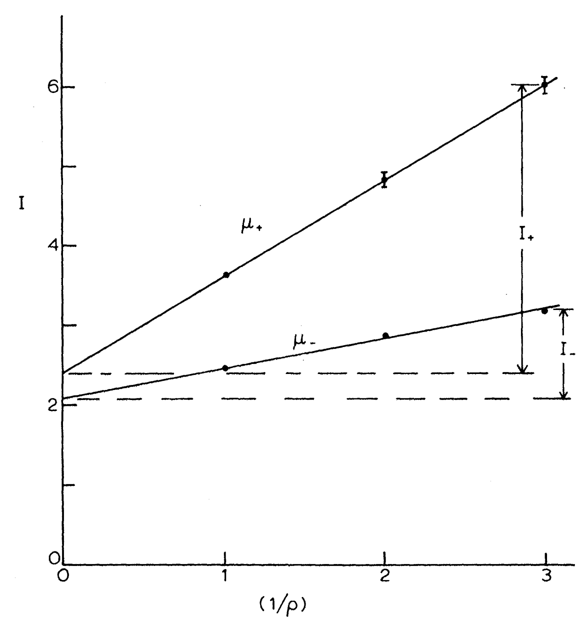

FIG. 1. The variation of intensity with respect to inverse target density of 180-GeV muons produced by the interaction of 400-GeV protons. The target is copper; the density-1 point refers to a solid copper target. The relative intensities of the muons from meson decay are indicated by the symbols I_+ and I_- and are proportional to the slopes of the lines. No corrections are required to the raw data pictures here.

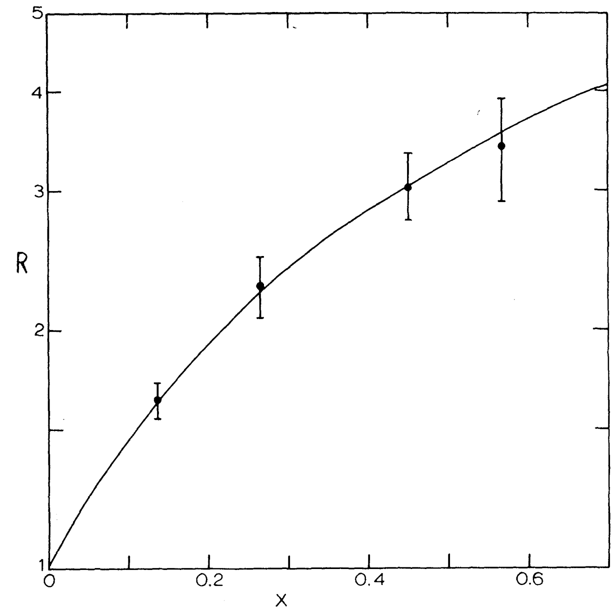

FIG. 2. The measured values of $R_m = I_+/I_-$ plotted against $x = E_\mu/E_p$ where $I_\pm$ represent the intensities of positive and negative muons from the decay of the mesonic component of the hadronic shower initiated by the interaction of 400-GeV protons with copper. The solid line represents the interpolation between points used in the calculations.

The muons from secondary cosmic rays represent muons from the decay of mesons produced at all transverse momenta. Although our detectors were placed in the forward direction, the large multiple Coulomb scattering in the target assembly gives the muons a mean transverse momentum of about 600 MeV and then we detect muons which represent a reasonable sample of the total cross section rather than production at 0°.

In order to deduce the results of a muon charge ratio measurement for the cosmic-ray energy spectrum, we assume that the charge ratios, defined as a function of x, do not depend appreciably on the proton energy and then we calculate the muon charge ratio for an incident proton spectrum weighted according to our knowledge of the primary cosmic-ray nucleon spectrum which we describe as $dN/dE_p = A \cdot E^{-\gamma}$, where γ is taken as 2.7 ± 0.1 and the value of the normalization constant A is not important. With this formulation of the incident nucleon spectrum, the muon charge ratio will be independent of muon energy and can be written as $R = I_+/I_-$ where

$$I_\pm = \int_0^I x^{\gamma-1} F_\pm(x)\, dx.$$

Here $F(x)$ represented the differential muon flux from the thick target which we could not measure reliably. However, the calculated ratio depends critically on the ratio F_+/F_-, which we do measure, and less sensitively on the variation of F with x. We then use a calculated value for $F_+(x)$ and take $F_-(x) = F_+(x)/R_m(x)$, where $R_m(x)$ was taken from the curve of Fig. 2. Numerical calculations of the variation of muon flux with energy were made in a manner similar to that described previously[1] using the measured meson spectrum from lower-energy proton-copper interactions. The calculated fluxes were fitted by the analytic form

$$F_+(x) = (A/x)\exp(-ax),$$

with $a = 10 \pm 1$. With this relation, we calculate $R = 1.625 \pm 0.09$ where the error includes our estimates of the uncertainties in our measurements and the uncertainties in the parameters a and γ. This number then represents the muon +/− charge ratio to be expected if a thick copper target with a small average density were bombarded by protons with an energy spectrum equivalent to that measured for the primary cosmic rays.

For a thick target of air, we should expect a slightly larger charge ratio. If we use the extensive data of Eichten *et al.*[6] on meson production from proton interactions with nuclei, we can estimate that the value of $R-1$ would be increased for air by $(5\pm 2)\%$, to give a value of 1.66 ± 0.09 for R. If the muon flux were due entirely to pion decay, the charge ratio for neutron interactions will be just $1/R$ from charge independence. However, about 20% of the muon flux is derived from the decay of charged K mesons, and since the K^+ and K^- are not members of the same isospin multiplet, the simple argument applicable to pions fails for K mesons. Since the cross section for hyperon production in nucleon-nucleon interactions is sizable, we can expect that the production of the $Y=+1$ K-meson doublet will be appreciably greater than for the $Y=-1$ doublet. Assuming, conservatively, that this ratio is $\sqrt{2}$ in the fragmentation region and that the ratio of intensities for the $T_3 = \frac{1}{2}$ and $-\frac{1}{2}$ states will be about the same for the two doublets, a charge ratio of 2.0 for K-meson production by protons leads to a value of 1.0 for production by neutrons; it is unlikely that the ratio will be smaller than 1.0; it may well be larger. Taking the muon charge as asymmetry for proton interactions as 1.66 ± 0.09, we deduce a charge ratio for neutrons of 1/1.44

$=0.695\pm 0.05$.

In these considerations we have made no correction for the reduced role of secondary processes in the atmosphere compared to that for a homogeneous thick target. Such a correction is model dependent: We believe that the correction is small, $\lesssim 0.04$. For any model, the correction is such that a homogeneous target must give *too small* a charge ratio and then our neglect of this factor is conservative. We have also assumed that the mean free path for decay of the mesons is large compared to the collision path. In the atmosphere, this is a good approximation for muon energies greater than critical energies of about 100 GeV for muons from pions and about 500 GeV for muons from K mesons. The comparison of muon charge ratios from copper with charge ratios from the atmosphere will then be adequate for muon energies above 500 GeV if scaling is valid in the fragmentation region. For muon energies between 100 and 500 GeV, the relative contribution of muons from K-meson decays will be less for the exponential atmosphere than for experimental targets. Since the charge ratio for muons derived from K-meson decays is, in general, larger than for muons from pion decays, this effect, taken alone, would lead to a slightly smaller charge ratio from cosmic rays than the ratios from a solid target. The relation between the solid-target accelerator measurements reported here and the charge ratio for cosmic-ray muons below 100 GeV is not at all straightforward, and we do not consider that our experiments are relevant to that problem.

Considering here only the flux of muons over 100 GeV (and then the flux of primary nucleons with energies in excess of 1 TeV), we use the charge ratio of 1.66 ± 0.09, derived from our measurements, and the commensurate value of $1/1.44 = 0.695\pm 0.05$ for neutrons, to find that neutrons must make up 0.25 ± 0.05 of the primary flux to account for the measured +/− muon charge ratio of 1.30 ± 0.03.[7] Conversely, the muon charge ratio predicted if the proportion of neutrons in the primary flux were 0.11, as found at much lower energies,[8] would be 1.50 ± 0.08, in poor agreement with the measured values but in good agreement with the value of 1.53 which we calculated previously[1] from the known hadron inclusive spectra and conservative estimates of nuclear effects, and in good agreement with the value of 1.45 derived similarly by Hoffman.[2] The conclusion discussed previously,[1,2] that the flux of heavy nuclei in primary cosmic rays at energies in excess of 1 TeV/nucleon is much larger than that observed at lower energies, is then supported by these measurements.

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[1]R. K. Adair, Phys. Rev. Lett. 33, 115 (1974).

[2]Recent calculations which are in agreement with the results of these measurements are presented by W. R. Frazer *et al.*, Phys. Rev. D 5, 1653 (1972); H. J. Hoffman, Phys. Rev. D 12, 82 (1975).

[3]G. D. Badhwar *et al.*, Phys. Rev. D 15, 820 (1977), have presented a calculation which is not supported by these measurements.

[4]L. B. Leipuner *et al.*, Phys. Rev. Lett. 35, 1613 (1975).

[5]L. B. Leipuner *et al.*, Phys. Rev. Lett. 36, 1101 (1976).

[6]T. Eichten *et al.*, Nucl. Phys. B44, 33 (1974).

[7]An average, for the range 100–1000 GeV, from H. Kasha *et al.*, in *Proceedings of the Fourteenth International Conference on Cosmic Rays, Munich, West Germany, 1975* (Max-Planck-Institut für Extraterrestrische Physik, Garching, West Germany, 1975), Vol. 6; J. M. Baxendale *et al.*, *ibid.*, p. 2011; K. Carstensen *et al.*, *ibid.*, p. 2082; T. L. Asatiani *et al.*, *ibid.*, p. 2024.

[8]S. Hayakawa, *Cosmic Ray Physics* (Interscience, New York, 1969), p. 538.