of NAL for their magnificent support of this experiment. We also wish to thank V. L. Fitch, S. B. Treiman, E. A. Paschos, and G. R. Farrar for valuable discussions. Finally, one of us (R.M.) wishes to thank NAL for its hospitality and support.

*Work supported by the National Science Foundation and the U. S. Atomic Energy Commission.

†On leave at NAL from the University of Geneva, Geneva, Switzerland.

[1]R. C. Lamb *et al.*, Phys. Rev. Lett. 15, 800 (1965).
[2]R. Burns *et al.*, Phys. Rev. Lett. 15, 830 (1965).
[3]P. J. Wanderer *et al.*, Phys. Rev. Lett. 23, 729 (1969).
[4]G. B. Bondarenko *et al.*, as cited by V. Lebedev in *Proceedings of the Sixteenth International Conference on High Energy Physics, The University of Chicago and National Accelerator Laboratory, 1972,* edited by J. D. Jackson and A. Roberts (National Accelerator Laboratory, Batavia, Ill., 1973), Vol. 2, p. 329.
[5]J. Christenson *et al.*, Phys. Rev. Lett. 25, 1523 1523 (1970).
[6]S. D. Drell and T. M. Yan, Phys. Rev. Lett. 25, 316 (1970).
[7]J. D. Bjorken, J. Phys. (Paris), Colloq. 34, C1-385 (1973).
[8]J. W. Cronin *et al.*, Phys. Rev. Lett. 31, 1426 (1973).
[9]For convenience we normalize to pions; the pions serve as a measure of all hadrons.
[10]G. R. Farrar, to be published.
[11]The yield of muons from the parton-antiparton annihilation process depends critically on the assumed antiparton distributions in the nucleon. The constraints on these distributions from inelastic electron and neutrino scattering make it unlikely that a parton model can account for the large observed muon yields.

Anomalous Muon and Hadron Charge Ratios in Secondary Cosmic Rays

Robert K. Adair
Yale University, New Haven, Connecticut 06520
(Received 18 March 1974)

Secondary cosmic-ray muon and hadron fluxes are calculated for particle energies above 200 GeV using accelerator data on inclusive hadron cross sections and the known primary flux. The gross differences between the calculated and measured muon and hadron charge ratios require radical reexamination of conventional views on hadron interactions or the neutron-proton ratio in the primary flux.

It is clearly possible to derive the characteristics of secondary cosmic-ray fluxes knowing the composition of the primary flux and the details of hadron-hadron interactions. In the energy region of 1000 GeV per nucleon, the primary flux intensity can be described by the relation[1,2]

$$dN/dE = A(\gamma - 1)E^{-\gamma}, \qquad (1)$$

where $A = 1.5 \pm 0.25$ cm^{-2} sec^{-1} sr^{-1}, $\gamma = 2.72 \pm 0.05$, and E, the energy per nucleon, is measured in GeV. Measurements of the charge spectrum[2] of the primaries at energy extending up to 400 GeV per nucleon indicate that about 89% of the nucleon flux are protons and 11% neutrons assuming that charge-1 particles are protons and charge-2 particles are α particles. Only hadron-hadron inclusive cross sections are necessary for an understanding of inclusive secondary fluxes; and proton-proton inclusive cross sections have been measured[3] up to laboratory energies of 1500 GeV at the CERN intersecting storage ring (ISR) facility, and meson interactions have been studied in accelerator experiments at lower energies. From this knowledge of the primary flux and the hadron interaction inclusive cross sections and the use of conventional assumptions concerning charge independence and factorization in the hadron-hadron fragmentation region, one can calculate secondary cosmic-ray fluxes precisely, in principle, if one neglects correlation effects or coherent effects in the projectile or target. Since these effects are not likely to be large, plausible estimates of these nuclear effects allow reliable calculations of the secondary fluxes. Although there is a long history of such calculations,[4] and the results presented here differ from many, but not all, of the previous conclusions, only now do we have sufficiently extensive and reliable data on the basic hadron interactions so that complete calculations can be made which are sufficiently accurate so that differences between the results of the calculations and measurements can confidently be ascribed to inadequacies in the conventional assumptions used in the calculations.

Since the mean transverse momentum of secondary particles is small, it is possible to assume that all secondary particles travel in the same direction as the primary particles. We can then adequately describe the hadron-hadron interactions in terms of the invariant inclusive cross sections $E_s\, d\sigma_s/dp_L$, where E_s is the energy and p_L is the longitudinal component of the momentum of the secondary particle s. In accord with the measurements, we assume that these invariant cross sections are approximately independent of the interaction energy or scale[5] but we use the scaling assumption only as a convenient way to interpolate and extrapolate the basic input cross sections taken from ISR data[3] and the results are neither sensitive to, nor do they test, scaling.

Any parametrization of the accelerator data is constrained by conservation laws: The conservation of energy requires

$$(1/\sigma_t)\textstyle\sum_s \int_0^1 E_s(d\sigma_s/dx)\,dx = E_i, \qquad (2)$$

where E_i and E_s are the primary and secondary particle energies, the summation is over all particle states s emitted in the forward direction in inelastic processes, σ_t is the total nonelastic cross section, and the integration is taken over x in the forward direction in the center-of-mass system, where $x = p_L/p_i$ and p_i is the center-of-mass momentum of an incident particle. We neglect processes in the backwards direction inasmuch as their contribution to the secondary fluxes is negligible.

The conservation of charge imposes the constraint

$$(1/\sigma_t)\textstyle\sum_s q_s \int_0^1 (d\sigma_s/dx)\,dx = q_i, \qquad (3)$$

where q_s is the charge of the secondary particle s and q_i is the charge of the beam particle. Here we assume that charge exchange is not important when the incident particle and the target particle have different charges—this follows from factorization, a more general assumption that particle distributions in the forward direction depend only on the identity of the beam particle and the backwards distribution depends only on the target particle.

The conservation of baryon number can be expressed as

$$(1/\sigma_t)\textstyle\sum_s B_s \int_0^1 (d\sigma_s/dx)\,dx = B_i, \qquad (4)$$

where B_i and B_s are the baryon numbers of the incident and secondary particles.

Another useful constraint derives from the precise measurements of the multiplicity M_q of charged particles produced in the interaction. We then require

$$(2/\sigma_t)\textstyle\sum_s |q_s| \int_0^1 (d\sigma_s/dx)\,dx = M_q, \qquad (5)$$

where M_q is the charged-particle multiplicity.

The experimental measurements of inclusive cross sections are made at specific angles and momenta and it is necessary to determine $E_s\, d\sigma_s/dp_L$ by integrating over the transverse momenta. For this purpose we assume that the cross sections take one of the following forms:

$$\text{(i)}\;\; E\,d^3\sigma/dp^3 = E\,d\sigma/dp_L(c^2/\pi)\exp(-c^2 p_t^{\,2}),$$
$$\text{(ii)}\;\; E\,d^3\sigma/dp^3 = E\,d\sigma/dp_L(b^2/2\pi)\exp(-bp_t); \qquad (6)$$

and we calculate $E\,d\sigma/dp_L$ from the measured values of $E\,d^3\sigma/dp^3$ as a function of x for $p_t = 400$ MeV/c. With the cross section known at this transverse momentum, the value of $E_s\, d\sigma_s/dp_L$ is determined almost independent of the choice of distribution or the value of a or b.

Since we are interested in the best values of $d\sigma/dp_L$ rather than fits to the differential cross sections $E\,d^3\sigma/dp^3$, standard least-squares techniques were inadequate and I established a "best fit" to the data subjectively. The cross sections so defined for production of various secondaries are shown graphically in Fig. 1 together with measurements of differential cross sections measured at $p_t = 400$ MeV multiplied by an appropriate factor as suggested above. The uncertainties in the integrations over the transverse momenta are approximately equal to the measurement errors shown on the figure. While estimates of antiproton and antineutron cross sections are included[3] and the choice of values for pion and K-meson cross sections reflect the results of the production and decay of strange baryons, the effect on the secondary fluxes of these production modes is not important.

Although the calculations reported here were made using Monte Carlo techniques where each particle and its tree of descendants were followed through their history, the numerical calculations were made in parallel with analytic calculations which depended upon appropriate weighted averages W_s of the inclusive cross sections for the production of the particles s:

$$W_s = (1/\sigma_t)\int_0^1 x^{\gamma-1}(d\sigma_s/dx)\,dx.$$

The flux of secondaries produced by the first interaction of the primary protons with protons

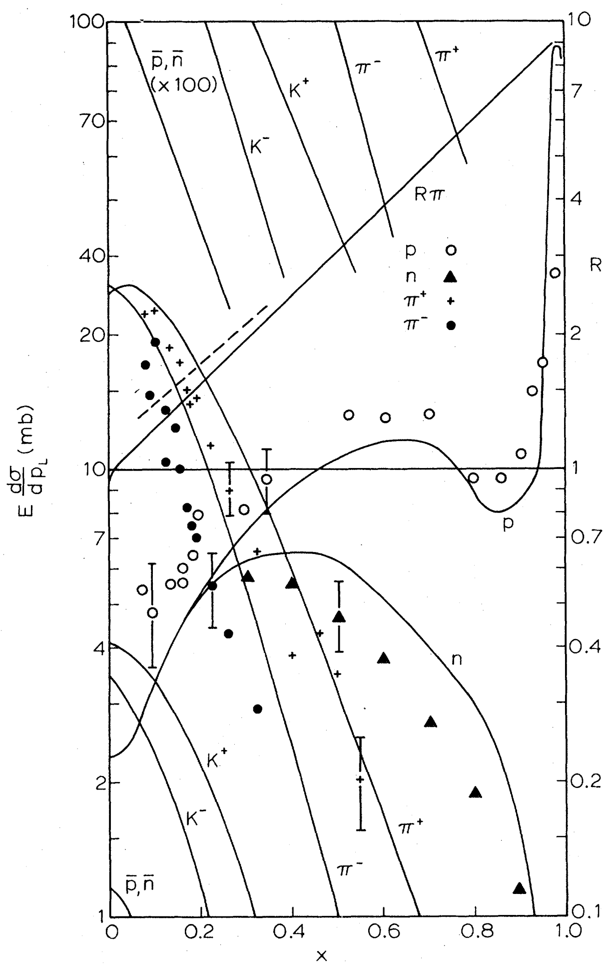

FIG. 1. The solid curves present the invariant proton-proton inclusive cross sections $E\,d\sigma/dp_L$ used in the analysis while the points represent values of $E\,d^3\sigma/dp^3$ measured at $p_t = 0.4$ GeV/c multiplied by 1.80 GeV^2. A solid line shows the π^+/π^- ratio from the curves while the dashed line gives the ratio from the data at $p_t = 0.4$ GeV/c.

would have the form

$$dN_s/dE_s = W_s\,dN/dE = W_s A(\gamma - 1)E_s^{\ \gamma}.$$

Values of W_s corresponding to the cross sections of Fig. 1 are given in Table I together with values of the total cross section for the production of the particles and the ratio of the mean momentum given to the secondary particle to the momentum of the primary in the center-of-mass system. Inasmuch as invariant cross sections scale, the production of secondaries near $x = 0$, and then the multiplicity and total cross sections for the production of secondary particles, increase logarithmically with energy. The total cross sections are then listed for a specific energy, 200 GeV.

TABLE I. Quantities which derive from the invariant cross sections used in the calculations. The cross sections are taken at 200 GeV lab energy.

Particle	σ_t (mb)	E_s/E_i	W_s
p	23.53	0.323	0.2426
n	14.43	0.120	0.0662
π^+	60.07	0.193	0.0624
π^0	55.18	0.160	0.0483
π^-	50.28	0.130	0.0347
K^+	8.55	0.035	0.0077
K^-	5.91	0.014	0.0036
$K_L^{\ 0}$	7.23	0.020	0.0056
$\bar{p}$	1.96	0.005	0.0012
$\bar{n}$	1.96	0.005	0.0012

Neutron cross sections are taken as the same as proton cross sections modified by charge symmetry, that is with n and p and π^+ and π^- reversed in Fig. 1, and with K^+ and K^- cross sections held equal to each other and to the mean of the K-meson cross sections from proton interactions. The production weights for pions produced by positive (or negative) mesons are taken to be the same as for protons (or neutrons) except that a value of 0.07 is added to the weight W_s corresponding to the incident particle to account for the leading particle effect connected with diffraction dissociation. The production of K mesons and nuclear pairs by mesons is neglected.

Since the incident primary nucleons interact with light atmospheric nuclei, not free nucleons, one must consider the complications imposed by nuclear effects. From the steepness of the primary spectrum and the large proportion of nucleons near the "edge" of light nuclei, we can be confident that single nucleon-nucleon interactions will be most important but multiple interactions cannot be disregarded. Almost independent of specific models, we can expect that multiple interactions will produce secondary particles with lower mean momenta and less charge asymmetry than single interactions. Since an incoherent model of multiple interactions, though implausible physically, has these properties and is easily treated in calculations, I chose to consider the nuclear effects by using a one-dimensional incoherent-interaction model of the nucleus where we treat the nucleus as a slab of nucleon gas with a thickness of h mean free paths for nucleons and $2h/3$ paths for mesons and follow the particles and their collision products through the slab. The mean free path for nucleon interactions producing mesons in the atmosphere was taken[6] as 92 g/cm^2 at 200 GeV, decreasing slowly (as the nucleon cross section increases) to 80 g/cm^2 at 2000 GeV. A best value of $h=1.0$ was found to give a hadron attenuation length equal to the measured length of 120 g/cm^2 and a meson mean free path at 200 GeV of 119 g/cm^2. In this model, 58% of the interactions are single nucleon-nucleon interactions which contribute about 81% of the secondary flux.

With this description of the nucleus, the hadron-hadron interactions, and the primary flux, the vertical flux of protons, neutrons, charged mesons, and K_L^0 mesons was calculated as a function of atmospheric depth, and the sea-level muon intensity and charge ratio was calculated for intrgral fluxes over 200 GeV. No approximations of any significance were required in the course of the numerical calculations. The energy range was chosen so that the spectra could be calculated using cross sections measured at the ISR with a minimal burden of extrapolation; the increases in total nucleon-nucleon cross sections which have been noted were not too important as they might be at higher energies, and nuclear effects and n-p charge exchange effects would not be expected to be important as they might be at lower energies.

While the hadron intensities and attenuation lengths and the muon intensities which are calculated are found to be in agreement with observations within experimental error, the calculated muon charge ratio of 1.53 is far larger than the measured value[7] of 1.30 ± 0.03. The calculated value is determined primarily by the ratio of the charged-pion weight functions of Table I where $W(\pi^+)/W(\pi^-) = 1.80$, as K-meson decays contribute only about 11% of the muon flux. We note from Fig. 1 that the pion charge ratio used in the calculations from the fitted data is appreciably smaller than the ratios derived from the unfitted data and we then regard our calculated value of the muon charge ratio of 1.53 as a conservative minimum; using the unfitted pion data, we get a muon charge ratio of about 1.64.

The calculated neutron-proton ratio at atmospheric depths from 600 to 800 g/cm^2 is 0.41. The measured neutral-to-charged hadron ratio in this range of energy and altitude[1] is about 0.70 ± 0.05 where there should be little contribution to the neutral flux besides neutrons but mesons should contribute substantially to the charged flux. The measured ratio is then a minimum while the calculated ratio is taken, conservatively, from fitted neutron cross sections which tend to be larger than the reported measurements as shown in Fig. 1.

It then seems impossible to reconcile the measured and calculated charge ratios for either the muon flux or the hadron flux; in each case there are more positive particles predicted than are measured. The experiments are straightforward and seem unimpeachable and the calculated results derive from the input data and well-defined, conservative, assumptions in a straight-forward way. I then conclude that the origin of the differences must be found in a breakdown of the basic assumptions used in the calculation. I list what seem to me to be the least unattractive possibilities: (a) The cosmic-ray neutron-proton ratio at energies near 1000 GeV per nucleon must be near 25:75 rather than 11:89 and hence a large fraction, about 20%, of the charge one flux must be deuterons. (b) At energies near 1000 GeV, there is very extensive charge exchange in p-n interactions so that the average total charge in the forward hemisphere in the center-of-mass system is much less than 1 and this effect extends into the fragmentation region. (c) Effects such as described in (b) might follow from coherent three-body effects (nuclear effects) which we cannot now anticipate.

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

[2]M. J. Ryan, J. F. Ormes, and V. K. Balasubrahmanyan, Phys. Rev. Lett. 28, 985 (1972).

[3]Valuable reviews are presented by J. C. Sens and by D. R. O. Morrison, in *Proceedings of the Fourth International Conference on High Energy Collisions, Oxford, England, 1972* (Rutherford High Energy Laboratory, Chilton, Didcot, Berkshire, England, 1972). Also see M. G. Albrow *et al.*, Nucl. Phys. B54, 6 (1973); A. Bertin *et al.*, Phys. Lett. 38B, 260 (1972); L. G. Ratner *et al.*, Phys. Rev. Lett. 27, 68 (1971); W. Bartel, W. Flauger, and H. Schopper, paper presented to the Second Aix en Provence International Conference on Elementary Particles, 1973 (unpublished).

[4]Typical calculations were presented by Y. Pal and B. Peters, Kgl. Dan. Vidensk. Selsk., Mat.-Fys. Medd. 33, No. 15 (1964); L. Volkova and G. T. Zatsepin, in *Proceedings of the Ninth International Conference on Cosmic Rays*, edited by A. C. Stickland (Institute of Physics and Physical Society, London, England, 1966); R. K. Adair, Phys. Rev. 172, 1370 (1968); W. R. Frazer, C. H. Poon, D. Silverman, and H. J. Yesian, Phys. Rev. D 5, 1653 (1972); Z. Garrafo, A. Pignotti, and G. Zgrablich, Nucl. Phys. B53, 419 (1973).

[5]R. P. Feynman, Phys. Rev. Lett. 23, 1415 (1959);

J. Benecke *et al.*, Phys. Rev. 188, 2159 (1969).
[6]G. Belletini *et al.*, Nucl. Phys. 79, 609 (1966).
[7]T. H. Burnett *et al.*, Phys. Rev. Lett. 30, 937 (1973); C. A. Ayre *et al.*, in *Proceedings of the Thirteenth International Cosmic Ray Conference, Denver, 1973* (University of Colorado, Denver, Colo., 1973); L. Leipuner *et al.*, in *Proceedings of the Thirteenth International Cosmic Ray Conference, Denver, 1973* (University of Colorado, Denver, Colo., 1973), and private communication.

Energy Dependence of the Double-Charge-Exchange Reactions $\pi^- p \to K^+\Sigma^-$, $K^- p \to \pi^+\Sigma^-$, and $K^- p \to K^+\Xi^-$†

C. W. Akerlof, P. K. Caldwell,* J. Koschik, R. Kotthaus,‡ D. I. Meyer, and B. Springett§
Physics Department, The University of Michigan, Ann Arbor, Michigan 48104
(Received 25 March 1974)

In an experiment at the Argonne National Laboratory zero-gradient synchrotron we have determined the forward differential cross sections for the double-charge-exchange reactions $\pi^- p \to K^+\Sigma^-$, $K^- p \to \pi^+\Sigma^-$, and $K^- p \to K^+\Xi^-$ for incident beam momenta up to 5 GeV/c. The production angle and momentum of the forward-going positive particle (π^+ or K^+) were measured with a high-resolution focusing wire-spark-chamber spectrometer and the two-body final states were selected by the missing-mass technique.

Our current understanding of high-energy hadron collisions is based on the idea that particle exchange provides the dominant force for interactions above a few GeV/c incident momentum. In time, the theoretical or phenomenological models which have embodied this primitive notion have grown steadily more ornate to allow greater freedom in fitting the expanding experimental data. Consequently, these models have become less testable by direct experiment and there have been no new guides to lead our physical intuition.

As a partial solution to this problem we have continued an earlier study[1] of the double-charge-exchange (DCX) reactions $\pi^- p \to K^+\Sigma^-$, $K^- p \to \pi^+\Sigma^-$, and $K^- p \to K^+\Xi^-$. The significance of these three reactions is that none of them can take place by the single exchange of any singly charged particle. Thus in the absence of normally large exchange forces we have a sensitive test for the existence of any of the three possible competing processes: (1) double particle exchange, (2) exotic single particle exchange, (3) intermediate s-channel resonance formation. In addition, by examining the energy behavior of the DCX cross sections we can hope to identify the dominant contribution in the asymptotically high-energy regime. This has been expected to be the double-particle-exchange diagrams which would yield differential cross sections with an $s^{-2.5}$ to s^{-3} behavior.[2]

The three reactions listed above also have some common properties which should set further limits on viable theoretical descriptions. For example, $\pi^- p \to K^+\Sigma^-$ and $K^- p \to \pi^+\Sigma^-$ are related by line crossing, so that these cross sections should be identical if induced by single exotic exchange and at least similar if induced by double particle exchange. $K^- p \to \pi^+\Sigma^-$ and $K^- p \to K^+\Xi^-$ have the same quantum numbers in the s channel, so that energy-dependent structure due to Y^* resonances should be expected in both reactions for the same incident momenta.

From our previous work we had experience with the experimental difficulties which beset measurements of the DCX reactions. Since the cross sections are all very small, an intense beam of incident particles is required on the hydrogen target. With available π/K ratios of the order of 200, the largest number of events could be obtained for the reaction $\pi^- p \to K^+\Sigma^-$, so that the experimental design concentrated on the detection of this particular channel. This required that a final-state K^+ be identified against an overwhelming background of pions and protons. At 5 GeV/c, for every K^+ from the reaction $\pi^- p \to K^+\Sigma^-$ there were 1000 π^+ and 200 protons within the missing-mass resolution of the experimental apparatus. To obtain sufficient rejection ratios against competing particle species, four Cherenkov counters were constructed to identify the positive particle in the final state. An unavoidable consequence was that the mass of the Cherenkov radiator to count kaons also produced substantial Coulomb scattering of the detected particle. Finally, since the cross section for the reaction $\pi^- p \to K^+\Lambda^0\pi^-$ rises steeply at the $\Lambda^0\pi^-$ threshold,