The results of the present work are in agreement with those of Ref. 1. Both excited states are characterized by $L=2$; in all three cases, the angular distributions fluctuate similarly to those of Ref. 1. Differences in slope and sharpness are consistent with the results of the microscopic distorted-wave Born-approximation fitting procedure. Similar results with respect to the energy dependence of (^{3}He,t) transitions in this mass region are obtained by Duhm et al.[3] in an investigation of the reaction ^{26}Mg(^{3}He,t)^{26}Al at 16- and 30-MeV incident energies. This comparison substantiates the assertion of a direct-reaction mechanism at 18-MeV incident energy, and thus that the results reported here can be explained primarily in terms of final-state configurations.

It appears, then, that useful nuclear structure information can be obtained by exploiting this property of the (^{3}He,t) reaction; while the reaction may not provide unambiguous spin assignments, it should be useful for studying the detailed structure of states of known spin.

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Charged-Particle Multiplicities of Proton-Proton Interactions Between 90 and 800 GeV*

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A cosmic-ray experiment at Echo Lake, Colorado, employing a 2000-liter liquid-hydrogen target together with spark chambers and an ionization calorimeter has been performed to study the interaction of protons with protons above 70 GeV. We report here the quantitative results on the distribution of secondary charged-particle multiplicity and the energy dependence of the average charged multiplicity.

Until recently the only source of information for ultrahigh-energy collisions of nucleons has been the study of the interactions of cosmic-ray hadrons with complex nuclei. This type of experiment, however, in addition to all the attendant difficulties of separating out the properties of the basic nucleon-nucleon interaction, has produced only a small number of events suitable for analysis, and these were frequently obtained without a direct measurement of the incident energy. We report here some quantitative results from an experiment that has studied the interactions of cosmic-ray hadrons with protons. This experiment, which consisted of a liquid-hydrogen target, spark chambers, and an ionization calorimeter, was carried out at Echo Lake, Colorado (3230 m), and produced approximately 1000 interactions above 70 GeV that were suitable for analysis.[1] The arrangement of the apparatus is shown in Fig. 1.

In operation, a charged cosmic-ray hadron that satisfied the trigger requirements passed

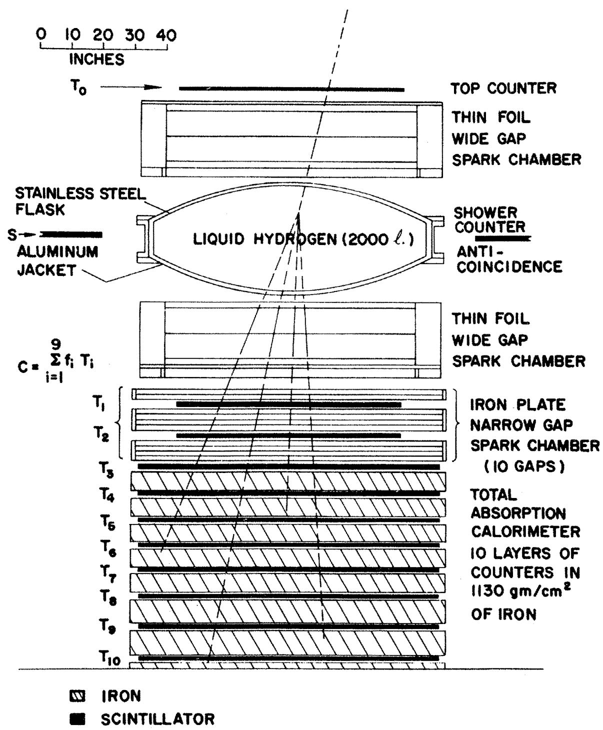

FIG. 1. Schematic vertical section of the Echo Lake cosmic-ray experiment.

through the top counter T_0 and through the upper wide-gap spark chamber, possibly interacted in the liquid-hydrogen target, continued on alone or with secondaries into the lower wide-gap spark chamber, and deposited 70 GeV or more in the ionization calorimeter. The wide-gap chambers were 2.0×2.0 m^2 in area and each had two 20-cm gaps formed from electrodes of 50-μm hardened aluminum. The target, in the shape of a short vertical cylinder with thin domes of spherical sections on either end, had a capacity of 2000 liters. The outer vacuum-jacket domes were 6.6-mm aluminum, while the inner flask domes were 1.2-mm stainless steel. The central thickness of the target was 80 cm and yielded an average path length of 55 cm in the liquid hydrogen (the boil-off rate was 70 liters per day and the target was refilled at ten-day intervals). The calorimeter was constructed from iron and plastic scintillator with a total thickness of 1130 g/cm^2. The upper 200 g/cm^2 had an area of 2.0×2.5 m^2 and was assembled as a ten-gap optical spark chamber, with 20 g/cm^2 between each pair of gaps, in order to detect accompanying neutrals and measure the range into the calorimeter of low-energy secondaries. The remaining 930 g/cm^2 had an area of 2.5 $\times 2.5$ m^2. Interspersed throughout the total depth of the calorimeter were ten plastic scintillation counters, placed at depths of 40, 120, 210, 330, 450, 570, 690, 810, 970, and 1130 g/cm^2. The top counter T_0 had an area of 1.8×1.8 m^2, and a "guard ring" of anticoincidence counters placed at the midplane of the target and used to suppress triggers accompanied by unrelated shower particles had a total area of 7.7 m^2. With this arrangement, the overall admittance of the apparatus was 0.9 m^2 sr after making appropriate fiducial cuts.

An event trigger fired the system of spark chambers, photographed them with 90° stero and a demagnification of 65:1 onto 35-mm film, and recorded the logarithm of the pulse height from each of the ten scintillation counters, together with some coded information, on magnetic tape. The energy of an incident hadron was determined from the pulse heights of the calorimeter counters. The nuclear-cascade energy loss sampled by the counters was normalized through calibration with cosmic-ray muons. Based on a Monte Carlo simulation of the cascade energy-loss processes, the energy resolution of the calorimeter was estimated to be about $\pm15\%$. In addition the absolute normalization was possibly uncertain by $\pm10\%$.[2]

From the data on hadrons which did not interact in the target it was ascertained that the integral flux was well represented by

$$N(>E) = (3\times10^{-7})E^{-2.0}\ (\mathrm{cm^2\ sr\ sec})^{-1},$$

with E in GeV. The slope of the spectrum is greater than that usually found because the anticoincidence counters reject a larger fraction of the higher-energy flux as they are more probably accompanied by secondaries from prior collisions in the atmosphere. While the incident flux consists mainly of protons, there is an admixture of pions (both positive and negative). A measure of this admixture was obtained from a run not including T_0 in the trigger, and scanning the iron-plate chambers in the upper parts of the calorimeter for neutron interactions. From these data the neutral/charge ratio was determined to be 0.63 ± 0.07 ($100<E<200$ GeV) and 0.70 ± 0.11 ($200<E<500$ GeV). With a proton/neutron ratio known from other sources to be about 1.2,[3] the pion/proton ratio is 0.32 ± 0.14 (<200 GeV) and 0.19 ± 0.16 (>200 GeV). The data do not otherwise distinguish between pions and protons, and in subsequent discussions the hadrons will be referred to as protons.

A high-energy proton incident on the hydrogen target and suffering an interaction produces a number of charged and neutral secondaries. These secondaries continue on mainly in the forward direction (in the lab system) and have a 5% probability of suffering further interactions in the remaining liquid hydrogen or walls of the containing vessel. There is a 3% probability per average track that charged secondaries produce δ rays along their path, and a 14% probability per γ that γ's from π^0 decay will convert to e^+e^- pairs. Also, some of the secondaries have large laboratory angles relative to the incident direction and thus miss the lower wide-gap spark chamber altogether, and some of the forward-going charged secondaries are too close together to be resolved in the lower wide-gap chamber.[4] To estimate the magnitude and energy dependence of these biases on the charged multiplicity distribution and the average charge multiplicity, we have generated high-energy proton-proton interactions with a Monte Carlo program using only the most general features of the high-energy models of Chew and Pignotti (CP)[5] and Feynman.[6] Specifically, the number of produced secondaries is a Poisson distribution, and the momentum distribution of the produced secondaries is given by

$$d^3N = (d^3p/E)e^{-Ap_T^2}$$

with a consequent logarithmic dependence of the average multiplicity on the energy. Here p_T is the transverse momentum of a secondary and E its energy. Also, for simplicity, all the produced secondaries were assumed to be pions. The resulting "observable" Monte Carlo distributions, including the distortions due to the physical and geometrical biases, fit the experimental multiplicity and angular distributions well and provided a means of correcting the data.[7] Elastic scattering is specifically excluded experimentally and in the calculations.

Since the Monte Carlo analysis indicated that the recoil nucleon misses the lower wide-gap spark chamber approximately 50% of the time, the charged multiplicity of an event was increased by one when the observed multiplicity was odd. The correction to each multiplicity, based on this prescription, was then determined from an evaluation of the fraction $N_{\text{gen}}(n)/N_{\text{obs}}(n)$, with $n = 2, 4, 6, \cdots$. Here, $N_{\text{gen}}(n)$ is the generated charge multiplicity and $N_{\text{obs}}(n)$ the "observable" charged multiplicity after inclusion of the physical and geometrical biases. The consequent corrections to the average charged multiplicity were very nearly independent of the incident energy and were approximately -0.4 prongs at each energy. The sensitivity of the wide-gap chambers falls off rapidly when the angle of a secondary relative to the vertical becomes larger than θ_0, and the corrections to the distributions depend weakly on θ_0. Our best measure of θ_0 is 40° and the corrections to the average multiplicity, based on this θ_0, have an uncertainty of $\pm 2.5\%$, representing the possible uncertainty in θ_0.

Figure 2 shows the charged-multiplicity distribution at three energies, plotting both the raw and corrected data. (In this and subsequent plots the data have been grouped into energy bins that are $\pm 0.2\bar{E}$ wide, where $\bar{E}$ is the average laboratory energy of the events in that bin.) The cor-

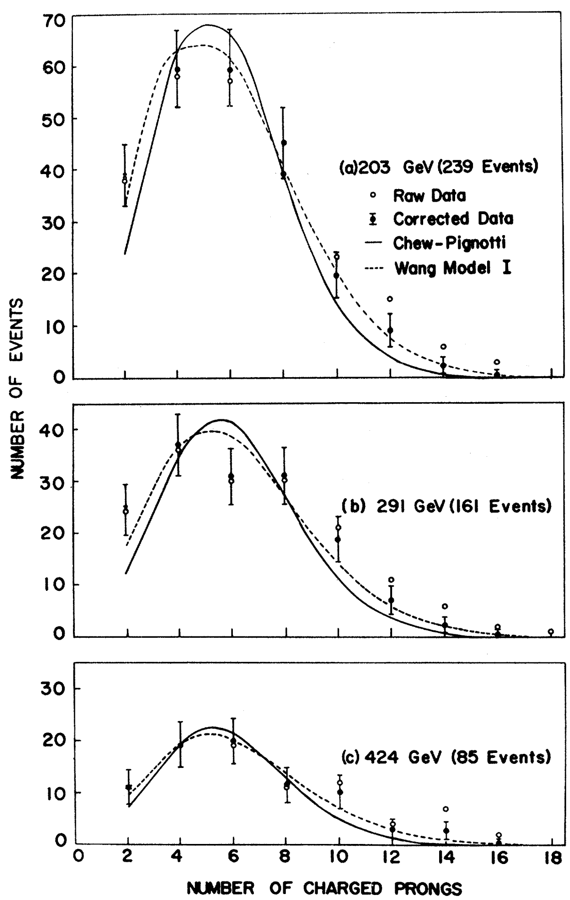

FIG. 2. Distribution in prong number for three energy bins. The solid curve is the Chew-Pignotti–model prediction, with the assumption of alternating isospin along the multiperipheral chain. The dashed curve is a Poisson distribution in pairs of produced charged particles. The two-prong corrected data contain a δ-ray subtraction explained in detail in Ref. 1. Elastic scattering not included.

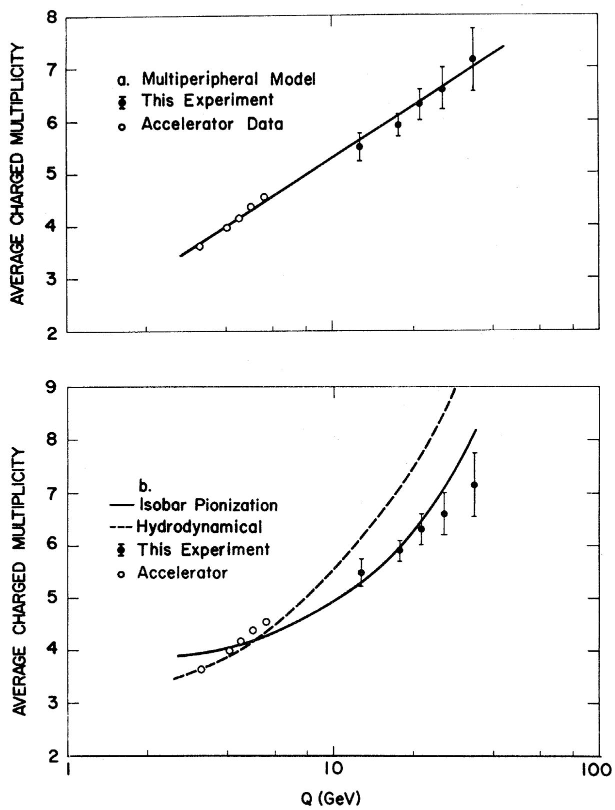

FIG. 3. Average charged-multiplicity fit by three models and described in the text. The accelerator data were taken from Ref. 9. The errors on the accelerator data for purposes of the fit were estimated from the quoted statistical and systematic errors given in this reference. The errors on the cosmic-ray data are statistical errors only. The abscissa Q is the center-of-mass energy available for particle production. The cosmic-ray data points correspond to the incident-proton energies 115, 203, 291, 424, and 684 GeV. Elastic scattering not included.

rected distributions were fitted by the conjecture of Wang[8] which predicts a Poisson distribution in pairs of produced charged secondaries, and to the multiperipheral model of Chew and Pignotti.[5] The Wang conjecture fits the data best but a modification of the CP model to π exchange and ρ production from ρ exchange and π production almost duplicates the Wang fit.

Figure 3(a) shows the average charged multiplicity $\bar{n}_c$ as a function of Q, the center-of-mass energy available for particle production, in GeV. Values of $\bar{E}$ for our data here are 115, 203, 291, 424, and 684 GeV. The data are remarkably linear in $\ln Q$, and a fit to $\bar{n}_c = A \ln Q + B$ gave $A = 1.41 \pm 0.20$ and $B = 2.04 \pm 0.19$ with a χ^2 of 4.6 for 8 degrees of freedom. At the cosmic-ray energies $\ln(E_p/m_p) \simeq 1.04 \ln(Q^2/2m_p^2)$, so that this fit gives $g_m^2 = 1.02 \pm 0.13$ for the value of the CP-model vertex constant. We note that when the average charged multiplicity is plotted against $\ln(E_p/m_p)$, the accelerator data have a larger slope than the cosmic-ray data and that this difference is largely removed by plotting the data against $\ln Q$.[10]

Figure 3(b) shows, for comparison, the data fitted by the hydrodynamical and isobar-pionization[3] models, where the expressions used were

$$\bar{n}_c = \tfrac{2}{3}(AE_p^{\ 1/4} - 2) + 1.4 \quad \text{(hydrodynamical)},$$

and

$$\bar{n}_c = \tfrac{2}{3}(A + BE_p^{\ 1/2}) + 1.4 \quad \text{(isobar pionization)}.$$

Here, in each case, it was assumed that on the average two thirds of the produced secondaries are charged and that 1.4 of the two nucleons are charged. The χ^2's were 112 for 9 degrees of freedom and 40 for 8 degrees of freedom, respectively.

In conclusion, we believe that the data indicate that at energies above 70 GeV the multiparticle final states of pp interactions have an average charged multiplicity that varies as $\ln Q$ and that the variation about the average is represented best by a Poisson distribution in pairs of produced charged particles.

It is a pleasure to acknowledge the contributions of W. R. Winter and J. Hicks of the University of Wisconsin Physical Sciences Laboratory. The continuing hospitality of Professor M. Iona and Denver University in making available the facilities of the High Altitude Laboratory has been invaluable. We have also benefitted from the use of the computing facilities of the National Center for Atmospheric Research. Finally, we gratefully acknowledge valuable participation in our program by other physicists, including R. Hartung, B. Dayton, P. D. Kearney, S. Lal, S. Mikamo, D. Pellett, S. Schindler, J. Wilkes, and P. Vishwanath.

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Connection Between Inelastic Proton-Proton Reactions and Deep Inelastic Electron Scattering*

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Following the idea that the electromagnetic and nuclear distributions behave similarly for large momentum transfers we examine the possibility of relating the deep inelastic electron scattering to large-momentum-transfer and high-energy inelastic proton-proton reactions.

A remarkable property of the elastic p-p scattering is that in the large-momentum-transfer region the differential cross section behaves similarly to the fourth power of the electron-scattering form factor,[1,2] i.e.,

$$\frac{d\sigma}{dt}=\left(\frac{d\sigma}{dt}\right)_{t=0}\left(\frac{1}{\mu}\right)^4 G_M^{\,4}(t), \quad t<M^2, \tag{1}$$

where t is the momentum transfer, $G_M(t)$ the proton magnetic form factor normalized to the total magnetic moment $\mu=2.79$ at $t=0$, and M the nucleon mass. As an explanation of this fact, Wu and Yang[1] have proposed that in the large-t region the nuclear matter distribution is essentially the same as the electromagnetic distribution and that in elastic p-p scattering one has the overlap of the two proton distributions giving rise to $G_M^{\,2}(t)$ in the scattering matrix element. Abarbanel, Drell, and Gilman[2] have suggested an even more specific mechanism for this large-t region, in which the scattering is deemed a consequence of an effective local four-fermion vector (or axial-vector) coupling with the universal form factor $G_M^{\,2}(t)$. Should these descriptions of the elastic p-p scattering be valid then we may easily extend their scope to make a direct comparison between the deep inelastic electron scattering and the inelastic p-p scattering which essentially amounts to replacing each elastic factor $G_M^{\,2}(t)$ by the inelastic strength factor νW^2.