Measurement of Charged-Hadron Multiplicities in Deep Inelastic Electron-Neutron Scattering*

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We report measurements of the charged-hadron multiplicity for electrons scattered by neutrons at momentum transfers up to $Q^2 = 6$ GeV^2, and for s up to 14 GeV^2. The average multiplicity shows little or no Q^2 dependence at fixed s, and except at low s it is consistent with being the same as the multiplicity in electron-proton scattering.

In a previous paper[1] we reported on the multiplicity of charged hadrons produced in deep inelastic electron scattering from hydrogen. We report here on a similar experiment using a deuterium target in order to measure the charged-hadron multiplicities in electron-neutron scattering.

The experimental arrangement is identical to the one used for the proton measurement. The analysis is also the same except for corrections to account for three additional effects: increased multiplicity due to spectator protons, kinematic smearing due to the Fermi momentum of the target nucleon, and final-state interactions. We have used a Reid soft-core S- and D-state deuteron wave function[2] in order to calculate these effects, as indicated below.

(1) The *spectator proton* is detected if it has sufficient range to pass through the material between the target and the hadron counters. The minimum detectable momentum varies somewhat with angle and is typically 260 MeV/c. According to the calculated deuteron momentum distribution, 5% of the nucleons have momenta greater than this. Thus the contribution to the observed mean multiplicity due to the spectator proton is 0.05.

(2) The *Fermi momentum* of the target nucleon shifts s, the actual square of the center-of-mass energy of the virtual-photon–nucleon reaction; it has no effect on Q^2, the square of the virtual-photon four-momentum. This has been taken into account by including the nucleon motion in the electron-scattering Monte Carlo calculation,[1] keeping track of both the true and apparent s. For each s bin in the data we then calculate the true average s to use in plotting and fitting the results for that bin.

(3) *Final-state interactions* between the electroproduced hadrons and the spectator nucleon have an effect on the deuteron multiplicity which is difficult to evaluate reliably. We have made a rough estimate[3] based on the deuteron wave function, known hadronic cross sections and multiplicities, and a plausible guess at the spatial development of the electroproduction multiplicity at short distances. The result implies a correction to the electron-neutron multiplicity equal to -0.3, varying only slightly with s and Q^2. Since this estimate is probably only good to within a factor of 2, we have *not* made the correction in our data.

The distribution of multiplicities in electron-neutron scattering is extracted from the deuterium data using the following relation:

$$\underline{D} = \frac{\sigma_p}{\sigma_p + \sigma_n} M_p \underline{P} + \frac{\sigma_n}{\sigma_p + \sigma_n} M_n \underline{N}, \qquad (1)$$

where $\underline{D}$ is a column matrix whose entries are the observed charged prong distribution from deuterium (fraction of events with $0, 1, 2, \ldots$ charged hadrons), $\underline{P}$ is a column matrix representing the true charged prong distribution from the proton $(1, 3, 5, \ldots)$ which we obtain from our previous experiment, and $\underline{N}$ is the desired true prong distribution from the neutron $(0, 2, 4, \ldots)$. σ_p and σ_n are the measured[4] proton and neutron total cross sections. We have used the parametrization $\sigma_n = (1 - 0.75x)\sigma_p$ with $x = Q^2/2m\nu$. M_p and M_n are Monte Carlo–generated matrices (for the proton and neutron, respectively) that transform the true prong distributions into the experimentally observed distributions. The i, j element of such a matrix is the probability that an event of true multiplicity i will be observed as a j-prong event (for more details, see Ref. 1). For each Q^2 and s bin, Eq. (1) is solved for $\underline{N}$ by least-squares fitting.

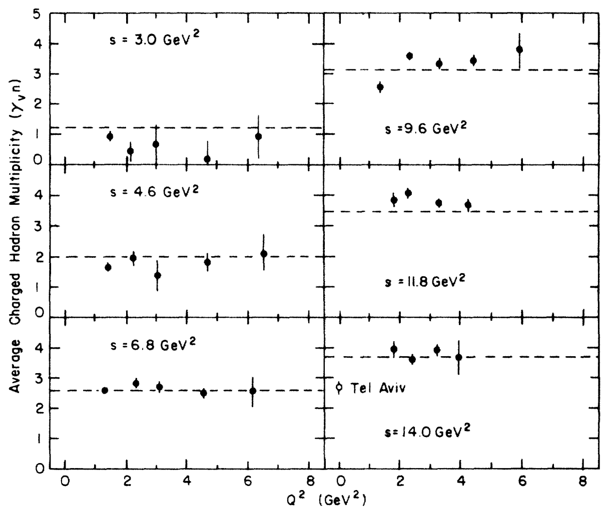

FIG. 1. Mean charged-hadron multiplicities in *en* inelastic scattering (virtual photon + neutron collision) as a function of Q^2 for several s values. Indicated errors are statistical; systematic errors are less than 0.3. The final-state interaction correction (about -0.3) has not been included. The photoproduction value at $s = 14.0$ GeV^2 is from Ref. 5. The dashed line shows *ep* multiplicities for comparison (Ref. 1).

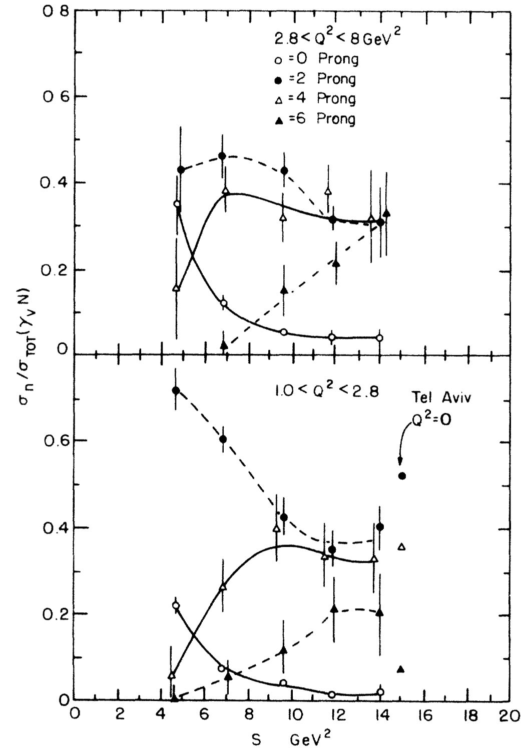

FIG. 2. The s dependence of the fractional cross sections for virtual photon + neutron → n charged hadrons (+ neutrals), plotted for two ranges in Q^2. Indicated errors are statistical; the systematic error is generally smaller. The points labeled "Tel Aviv" are from a photoproduction experiment (Ref. 5).

Figure 1 shows the corrected average charged-hadron multiplicity $\bar{n}$ as a function of Q^2 for several s values. For comparison, the dashed line indicates the average value of $\bar{n}$, for each s, from our proton experiment.[1] Also shown, in the highest s bin, is a photoproduction result obtained by a University of Tel Aviv group from a deuterium bubble chamber experiment at the Stanford Linear Accelerator Center.[5] The indicated errors are statistical errors only, propagated through the fitting procedure. The systematic errors are probably less than 0.3 in the average multiplicities. The s dependence can be made to fit either the $a+bs^{1/4}$ of the thermodynamic models[6] or the $a+b\ln s$ of short-range order in rapidity.[7] Our data rule out, however, any comparably rapid dependence on Q^2, such as the scaling prediction $a+b\ln\omega$ of the soft-field-theory parton model[8] or the multiperipheral model.[9]

Figure 2 shows our relative cross sections for zero-, two-, four-, and six-prong events as a function of s for two ranges in Q^2. The photoproduction results[5] are also shown in the lower Q^2 range. The same general behavior is seen in these data as is seen in corresponding proton data[1]; that is, very little dependence on Q^2 except perhaps at low s and low Q^2, where the zero- (or one-, in the *ep* case) prong relative cross

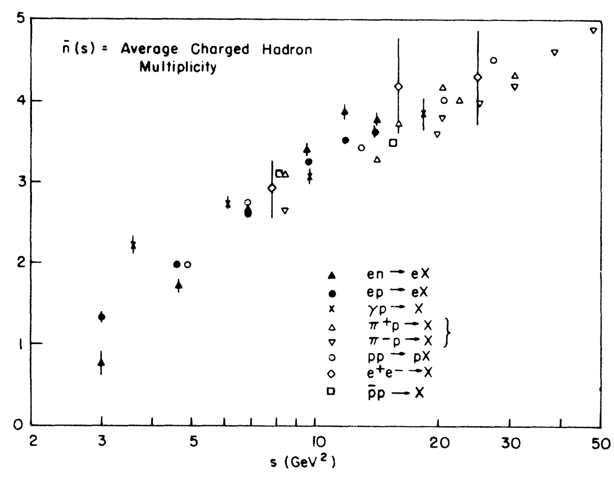

FIG. 3. The s dependence of the average charged multiplicity of the state X in the reactions $en \to eX$ (this experiment), $ep \to eX$ (Ref. 1), $\gamma p \to X$ (Ref. 10), $\pi p \to X$ (Ref. 11), $pp \to pX$ (Ref. 12), $e^+e^- \to X$ (Ref. 13), and $\bar{p}p \to X$ (Ref. 14). In each case s is the square of the center-of-mass energy of the state X. The electroproduction data (*en* and *ep*) are averaged over Q^2.

section increases with Q^2, while the two- (or three-) prong fraction decreases.

The s dependence (averaged over Q^2) for the charged multiplicity from both neutron and proton targets is shown in Fig. 3. Also presented are the results from photoproduction,[10] πp scattering,[11] the recent experiment on associated multiplicity in $pp \to pX$,[12] e^+e^- colliding beam results,[13] and $\bar{p}p$ data.[14] The impressive thing about this comparison is that, except at low s, where one might reasonably expect individual differences, the value of the average multiplicity and its s dependence are remarkably similar, independent of what the colliding particles are, and, in fact, independent of how far off the mass shell they are. This suggests that although the scattered electron may transfer energy and momentum to a single pointlike constituent of the nucleon, the excitation is rapidly thermalized and the final-state multiplicity depends only on center-of-mass energy, in the same way as in any other high-energy collision.

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Space-Time Structure of Hadronic Collisions and Nuclear Multiple Production*

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Nuclear interactions at high energy are sensitive to the space-time structure of basic hadronic collisions. A model of this structure is proposed; it provides a parameter-free account of National Accelerator Laboratory and cosmic-ray emulsion data, which shows that the multiplicity of mesons produced in nuclei exceeds that in hydrogen by an energy-independent ratio remarkably close to unity.

Let τ be a time that characterizes a pp collision in its c.m. frame. In the target rest frame τ is dilated to[1] $\tau' = \tau(E/2m)^{1/2}$. Should this collision occur in a nucleus, and E be sufficiently large, τ' will exceed[2] the nuclear mean free path λ. At the point the nuclear process becomes sensitive to the short-time behavior of hadronic interactions, and yields information that cannot be inferred directly from the S-matrix elements observed in hydrogen experiments.

One might have expected nuclear multiple production to be a messy phenomenon, but it is enigmatically simple: The mean multiplicity and angular distributions of relativistic secondaries