clear whether we arrive at the same answer. However, Professor Feynman informs us that his result is meant to refer to the integral energy loss up to $(1-x)=\bar{\epsilon}/E$, which then agrees with our Eq. (5).

[7]See, for example, D. R. Yennie, in *Brandeis Summer Institute 1962 Lectures in Theoretical Physics: Elementary Particle Physics and Field Theory*, edited by K. W. Ford (Benjamin, New York, 1963), Vol. I.

[8]E. Fermi, *Nuclear Physics* (Univ. of Chicago Press, Chicago, Illinois, 1950); p. 43. More recently see J. D. Jackson, *Classical Electrodynamics* (Wiley, New York, 1962), Chap. 15.

[9]H. A. Dobrotin, in *High Energy Physics in Cosmic Ray Study at the Herceg-Novi School*, edited by M. Nikolic (Laboratoire de Physique Corpusculaire, Strasbourg-Cronenburg, France, 1970), Chap. III.

What is the Charge of a Parton?*

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It is shown that present inclusive electroproduction experiments cannot distinguish the fractionally charged quark model from certain multitriplet models with integral charges, e.g., the Han-Nambu three-triplet model, which contain additional internal degrees of freedom and predict new "charmed" hadron states which have not yet been observed. Both models are shown to predict identical results if no "charmed" states are produced, and very similar results unless charmed particle production appreciably affects the inclusive cross section.

A number of recent studies have attempted to obtain information on the electric charge of the basic constituents (partons) of hadrons by analyzing inelastic electron-scattering experiments.[1,2] In particular there have been attempts to distinguish[3] between the Gell-Mann–Zweig (GMZ) quark model with fractionally charged particles and other models that use fundamental triplets of integral charge.[4,5] The purpose of this note is to point out a basic incompatibility between the parton and multitriplet models and to suggest that analysis of inclusive experiments does not provide a useful method for distinguishing between the fractional-charge quark model and the models with integral-charge triplets.

Hadron models that avoid third-integral charges by introducing several triplets with integral charge also introduce an additional degree of freedom sometimes called *charm*. This new degree of freedom results in two relevant effects: (1) The existence of "charmed particle states" is predicted, but no such particles have yet been observed. The only explanation for the failure to observe such particles is that present experiments have not yet reached an adequate energy. (2) The constituents of the normal observed hadron states have strong charge-exchange interactions, and their integral charges fluctuate as a function of time. The instantaneous charge values are always integral; the values averaged over the fluctuations are the same as the fractional charges of the GMZ quark model.

The parton model assumes that partons have well-defined instantaneous properties, including electric charge, which are "frozen" for the duration of the collision under consideration. An experiment in this model measures the instantaneous parton charge. This parton picture is consistent with multitriplet hadron models only if the collision is very fast compared to the charge-exchange processes that cause charge fluctuations.[6] In the specific example presented below, this consistency condition cannot be met unless there is considerable charmed-particle production. This hadron model with integral-charge triplets cannot be distinguished from the Gell-Mann–Zweig model with fractional charges by any analysis of inclusive electroproduction experiments below the threshold for charmed-particle production. In this hadron model, appreciable production of charmed particles is a *necessary condition* for the validity of the simple parton model.

Consider the π^+. In the conventional quark model the π^+ is composed of a p-type quark and an $\bar{n}$-type antiquark, i.e.,

$$|\pi^+\rangle = |p\bar{n}\rangle. \tag{1a}$$

The electric charges are

$$Q_p = +\tfrac{2}{3}, \quad Q_{\bar{n}} = +\tfrac{1}{3}, \quad Q_{\pi^+} = 1. \tag{1b}$$

In various three-triplet models, such as the one of Han and Nambu,[4] there are three different types of p quarks which we denote by p_1, p_2, and p_3; and similar considerations apply for n and λ quarks. In this model the π^+ wave function is the symmetric combination

$$|\pi^+\rangle = 3^{-1/2}|p_1\bar{n}_1 + p_2\bar{n}_2 + p_3\bar{n}_3\rangle, \tag{2a}$$

and the electric charges of the constituents are

$$Q_{p_1} = Q_{p_2} = +1, \quad Q_{\bar{n}_1} = Q_{\bar{n}_2} = 0, \tag{2b}$$

$$Q_{p_3} = 0, \quad Q_{\bar{n}_3} = +1. \tag{2c}$$

The state (2a) is a mixture of components of two types, one with a charged quark and an uncharged antiquark, and one with a charged antiquark and an uncharged quark. The instantaneous quark and antiquark charges are always integral. However, the average quark charge in the wave function (2a) is $+\frac{2}{3}$ and the average antiquark charge is $+\frac{1}{3}$, exactly as in the fractional-charge quark model (1a). The multicomponent wave function (2a) implies the existence of charge-exchange interactions that cause the parton charge to fluctuate between integral values in such a way that the average value is third integral. An attempt to measure the electric charges of the constituents of a pion described by the wave function (2a) may determine either the *instantaneous* charge or the *average* charge.[7]

An experiment that measures only the average charge gives the same result as for the fractional-charge wave function (1a). In a space-time description of the experiment, the parton charge is measured only if the time scale of the experiment is sufficiently rapid to follow the instantaneous charge fluctuations and catch the wave function (2a) instantaneously in one of its three components. This depends on the experimental conditions and the rapidity of the fluctuations.

The following argument suggests that an experiment is "fast enough" only if it is at high enough energy to produce charmed particles. From three kinds of p quarks and three kinds of $\bar{n}$ antiquarks, nine quark-antiquark states can be made with the isospin and hypercharge of the π^+. Only one such state is observed as the physical pion. The other eight must be "charmed states" which have such a high energy that they have not yet been observed. The excitation energy of these states is related by the usual uncertainty-principle argument to the characteristic time of the flipping of the components of the state (2a).

A formal proof of the relation between instantaneous-charge measurement and charmed-particle production follows simply from the transformation properties of the wave function (2a) under an SU(3) group acting in the space of the indices 1, 2, and 3. This group, which we call the "new SU(3)," is different from the conventional SU(3) which transforms states between the p, n, and λ labels. The standard treatments of the three-triplet model put the two SU(3) groups into an SU(3) $\otimes$ SU(3) group.

The wave function (2a) is clearly invariant under all transformations in the three-dimensional space of the indices 1, 2, and 3. It is therefore a scalar (i.e., a singlet) in the new SU(3). The other eight $p\bar{n}$ states constitute an octet in the new SU(3). This result, shown explicitly for the π^+, is true for all the observed hadron states in this three-triplet model. They are all singlets in the new SU(3) group, which involves transformations only in this new degree of freedom and does not affect other properties. The new SU(3) singlet states in this model are in one-to-one correspondence with the states of the conventional quark model and can be adjusted to have very similar properties. The states in other new SU(3) representations have no counterpart in the quark model and remain to be found experimentally.[7]

We shall now prove that this three-triplet model cannot be distinguished from the Gell-Mann–Zweig fractional-charge quark model in processes in which the transition matrix element is proportional to the matrix element of the electric-current operator between the initial and final states, and in which there is no appreciable production of final states that are not singlets in the new SU(3). This proof applies to any version of the three-triplet model in which the ordinary observed hadrons are singlets in the new SU(3), and it does not require the specific form of the wave function (2a). It applies as well to models in which each hadron contains a large sea of triplet-antitriplet pairs in addition to the "valence triplets"—so long as the sea is in a singlet of the new SU(3). It also includes models[5] that attempt to fit some observed resonances with peculiar properties into other representations of the new SU(3). So long as the production of these resonances contributes only a small part of the inclusive cross section, the production of states that are not singlets in the new SU(3) is still negligible.

The electric charge in this three-triplet model can be written as the sum of two terms,[4,5] i.e.,

$$Q = Q^{\mathrm{GMZ}} + Q^{\mathrm{A}}, \tag{3a}$$

where the quark charge Q^{GMZ} given by the Gell-

Mann–Zweig model is

$$Q_p^{\mathrm{GMZ}} = +\tfrac{2}{3}, \quad Q_n^{\mathrm{GMZ}} = Q_\lambda^{\mathrm{GMZ}} = -\tfrac{1}{3}, \tag{3b}$$

and the anomalous contribution Q^{A} to the charge is

$$Q_1^{\mathrm{A}} = Q_2^{\mathrm{A}} = +\tfrac{1}{3}, \quad Q_3^{\mathrm{A}} = -\tfrac{2}{3}. \tag{3c}$$

The Gell-Mann–Zweig charge Q^{GMZ} is independent of the indices 1, 2, and 3 depends only on the ordinary SU(3) variables p, n, and λ. The anomalous charge Q^{A} is independent of the ordinary SU(3) variables and depends only on the new SU(3) indices 1, 2, and 3. By inspection, Q^{GMZ} transforms like a member of an octet under the ordinary SU(3) and like a singlet under the new SU(3), whereas Q^{A} is a singlet under the ordinary SU(3) and is a pure octet with no singlet component under the new SU(3).

A similar decomposition holds for the electromagnetic current

$$J_\mu = J_\mu^{\mathrm{GMZ}} + J_\mu^{\mathrm{A}}. \tag{4a}$$

The current is defined in the usual way in terms of triplet Dirac spinors $\Psi_{\alpha i}$, with $\alpha = p, n, \lambda$ and $i = 1, 2, 3$. That is,

$$J_\mu = \sum_{\alpha i} \overline{\Psi}_{\alpha i} \gamma_\mu Q_{\alpha i} \Psi_{\alpha i}; \tag{4b}$$

and thus

$$J_\mu^{\mathrm{GMZ}} = \sum_{\alpha i} \overline{\Psi}_{\alpha i} \gamma_\mu Q_\alpha^{\mathrm{GMZ}} \Psi_{\alpha i}, \tag{4c}$$

$$J_\mu^{\mathrm{A}} = \sum_{\alpha i} \overline{\Psi}_{\alpha i} \gamma_\mu Q_i^{\mathrm{A}} \Psi_{\alpha i}. \tag{4d}$$

Consider an electromagnetic process in which the cross section for production of any given final state F from an initial state A is proportional to the square of the transition matrix element of J_μ. The total cross section is

$$\sigma_{\mathrm{tot}} = \sum_F C_F |\langle F | J_\mu | A \rangle|^2, \tag{5}$$

where C_F is a proportionality factor.

If A is an ordinary particle which is a singlet under the new SU(3), transitions to final states F_0 that are also singlets can come only from the singlet part of the current, while transitions to octet states F_8 can come only from the octet part. Thus,

$$\sigma_{\mathrm{tot}} = \sigma_0 + \sigma_8, \tag{6a}$$

where

$$\sigma_0 = \sum_{F_0} C_{F_0} |\langle F_0 | J_\mu^{\mathrm{GMZ}} | A \rangle|^2, \tag{6b}$$

$$\sigma_8 = \sum_{F_8} C_{F_8} |\langle F_8 | J_\mu^{\mathrm{A}} | A \rangle|^2. \tag{6c}$$

Equations (6) show that if only ordinary singlet particles are produced, $\sigma_8 = 0$ and the total cross section is determined entirely by J^{GMZ}. There is then no possibility of detecting the difference Q^{A} between the instantaneous parton charge and the average charge given by the quark model.[8]

Values differing from quark-model predictions can be obtained only when σ_8 is appreciable. A discrepancy of 10% from a cross section consistent with GMZ quark charges can be obtained only if charmed particles are produced in at least 10% of the events.

Thus, inclusive experiments whose results agree with GMZ predictions cannot rule out integral-charge triplet models if no charmed-particle production is observed. On the other hand, if charmed particles are really produced in 10% of the events, it is probably easier and more convincing to observe them directly than to pin down a 10% change in the total cross section.

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[5]O. W. Greenberg and C. A. Nelson, Phys. Rev. Lett. 20, 604 (1968), and Phys. Rev. 179, 1354 (1969).

[6]The presence of internal symmetries raises subtle points in the parton picture. H. J. Lipkin, in Proceedings of the Conference on Particle Physics, Irvine, California, 1971 (American Institute of Physics, New York, to be published), discusses the example of G-parity conservation. In deep-inelastic scattering on a pion, produced by the isovector component of the vector current, the initial state has odd G and only odd numbers of pions are allowed in the final state. In the calculation of the total cross section as forward Compton scattering the most naive form of impulse approximation would violate G conservation in the intermediate state between absorption and re-emission of the photon. The suppression of the even-pion final states can be described in the parton model only by including coherent addition of symmetrized amplitudes.

[7]An instructive analog is a world built of deuterons,

in which all low-lying hadron states have zero isospin. Below the threshold for production of states with nonzero isospin, only the isoscalar component of the electromagnetic current would be observed. This isoscalar probe would not distinguish between proton and neutron. Low-energy experiments would indicate a deuteron made of two identical spin-$\frac{1}{2}$ nucleons, each with charge $\frac{1}{2}$, and peculiar statistics allowing two identical particles in a symmetric state. Only after the excitation of the isovector states of the two-nucleon system would it be clear that there was a hidden degree of freedom and two kinds of nucleons with integral charges.

[8]This result is expected, since the three-triplet model was constructed to give all the Gell-Mann–Zweig properties of observed particles. Given a set of hadron states in the conventional quark model, corresponding hadron states in the three-triplet model can be constructed for which the matrix elements of the electromagnetic current operator are identical to those of the quark model.

Photoproduction and Forbidden Decays of φ Mesons*

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Photoproduction of φ mesons from hydrogen and carbon was studied at 5.2 GeV by observing $\varphi \to K^+K^-$ decays. The results show that φ's are produced diffractively with a φ-nucleon cross section $\sigma_{\varphi N} = 9.8^{+2.9}_{-3.3}$ mb. In addition, 80 000 pion pairs were measured to search for the G-parity–nonconserving decay $\varphi \to \pi^+\pi^-$. Assuming complete interference between $\rho \to \pi^+\pi^-$ and $\varphi \to \pi^+\pi^-$, we found an upper limit of $\Gamma_{\varphi \to 2\pi}/\Gamma_{\varphi \to \text{all}} = 2.7 \times 10^{-4}$ at the 95% level.

In an experiment performed at the DESY 7.5-GeV electron synchrotron we studied the production of $\varphi \to K^-K^+$ and searched for the decay of $\varphi \to \pi^+\pi^-$, both at forward angles, from

$$\begin{array}{l} \gamma + p \to p + \varphi + \cdots \\ \qquad\quad \llcorner\!\to K^+K^- \\ \gamma + C \to C + \varphi \\ \qquad\quad \llcorner\!\to K^+K^- \\ \gamma + C \to C + \varphi \\ \qquad\quad \llcorner\!\to \pi^+\pi^- \end{array} \qquad (1)$$

For K^-K^+ pairs, measurements were made at the fixed K^-K^+ laboratory momentum of $p = 5.2$ GeV with $K_{max} = 6.2$ GeV. The $\pi^+\pi^-$ pairs were detected at a fixed laboratory momentum of 6.7 GeV with $K_{max} = 7.4$ GeV. The object of the experiment was twofold: (1) to provide an accurate determination of the forward production cross section of φ from hydrogen and carbon for comparison with the diffraction model and to extract the φ-nucleon cross section $\sigma_{\varphi N}$ from vector-dominance models for comparison with quark-model predictions[1]; (2) to search for the decay $\varphi \to \pi^+\pi^-$ and compare it with our measured decay $\omega \to \pi^+\pi^-$ and various theoretical models.[2]

φ and ω mesons both decay strongly into three pions. Their 2π decay mode does not conserve G parity. The order of magnitude expected for $\varphi \to 2\pi$ and $\omega \to 2\pi$ decay amplitudes, as compared with $\rho \to 2\pi$ decay amplitude, is the fine-structure constant α. Such a result can be visualized as a one-photon–exchange mechanism where φ (or ω) $\to \gamma \to \rho \to 2\pi$ with corresponding partial widths $\Gamma_{\omega \to 2\pi} \approx 10$ keV, $\Gamma_{\varphi \to 2\pi} \approx 0.6$ keV. Our previously measured width $\Gamma_{\omega \to 2\pi}$ is a factor of 10 larger than the simple predicted value. It is of interest to see if the $\varphi \to 2\pi$ width is also correspondingly larger.

The K^+K^- pairs were detected by a double-arm magnetic spectrometer which has been described in a previous publication.[3] The separation of K^+K^- from the background of $\pi^+\pi^-$ and e^+e^- was accomplished by four large-aperture threshold Cherenkov counters and two lead-Lucite shower counters. Protons were rejected by time-of-flight techniques. The contaminations of π, p, and e in the final $\varphi \to K^+K^-$ events were $< 1.5\%$. The accidentals were typically 1–2%. The acceptance of the apparatus was calculated by the Monte Carlo method, in which multiple scattering and both two-body and three-body decays of the