In addition to emulsion data, we also measured time of flight with the current collector screens. We generally observe two large positive pulses 5 to 8 nsec wide and 10 nsec apart. The first pulse is generally lower in current than the second by a factor of 4. The β of these pulses correspond to the proton peaks in the spectrometer, with the β of second pulse lower than the first. With gases other than hydrogen in the drift region, the pulses are followed by a positive tail 60 to 80 nsec long. Presumably the tail contains accelerated gas ions. If the particles in the first pulse are assumed to be accelerated near the anode, then we can relate the time of acceleration of the first proton pulse to the arrival of the electron stream at the first Rogowski coil. Delays of 35 ± 5 nsec for air at 10 μm and 5 ± 5 nsec for hydrogen at 200 μm are found, consistent with the time required for force neutralization of the electron beam as also observed by Graybill and Uglum.[3]

In summary, we observe that protons and gas ions are accelerated when a relativistic electron stream is propagated through a gas-filled region; the protons are accelerated in multiple pulses, with momentum spreads $\leq 10\%$; the proton momentum is the same for N_2 and H_2 filling gases; the proton momentum but not flux is reproducible from pulse to pulse within 10%, with total accelerated ion fluxes of 10^{13} to 10^{15} ions/electron stream pulse. If the nitrogen ions comprising the low-momentum peak are +4 or +5, which is consistent with our upper limit on track length, then it appears that they have the same energy-to-change ratio as the lowest proton momentum peak observed with the spectrometer, consistent with the time-of-flight data of Graybill and Uglum.[3] It would appear that this dependence upon z and the narrow proton momentum spectrum place severe constraints on an ion acceleration model.

We would like to acknowledge the assistance of Dr. H. Heckman and his staff at the Nuclear Emulsion Group, Lawrence Radiation Laboratory, Berkeley, with the nuclear emulsions, and for providing the plates used during the experiment. We thank Don Pellinen for invaluable aid in the initial stages of the investigation.

*Work supported in part by the U. S. Atomic Energy Commission.

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DUALITY, QUARKS, AND INELASTIC ELECTRON-HADRON SCATTERING*

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(Received 10 October 1969)

A model for high-energy hadron reactions is proposed, incorporating ideas borrowed from the duality scheme of strong interactions and from the quark version of the parton model for inelastic electron-hadron scattering. Experimental tests of the model are discussed.

Some time ago we proposed a simple model[1] for inelastic electron-hadron scattering, in which we applied ideas borrowed from strong interaction dynamics[2] to the absorption of virtual photons by hadrons. The model suggested that (i) the Pomeranchuk singularity dominates high-energy photoabsorption cross sections; (ii) the q^2 dependence of the Pomeranchukon contribution is different from that of the other trajectories; and (iii) as q^2 increases, contributions of s-channel resonances or (equivalently) "ordinary" t-channel exchanges decrease very rapidly, leaving the Pomeranchukon term as the only important term even at relatively low energies.

A different model was developed by Bjorken and Paschos.[3,4] These authors view high-energy inelastic electron-hadron scattering as a superposition of interactions of the incident electron with objects ("partons") which, at an infinite momentum frame, look like point charges within the hadron. A specific version of this model[3] identifies the "partons" as quarks and considers the nucleon to be a three-quark structure accompanied, in the infinite-momentum frame, by an "infinite sea" of $q\bar{q}$ pairs.

In this paper we propose an extended version of our "diffractive" model,[1] into which many of the ideas of the parton model[3] are incorporated. We show that certain ingredients of the two approaches can be merged, leading to an attractive picture of high-energy scattering and to many testable predictions.

Our model is based on the idea that all hadronic amplitudes can be approximately described in terms of two (additive) parts, and that within the frame-works of different approaches, these two parts have different, but consistent, descriptions. We utilize the consistency constraints imposed by the various approaches on each other to derive our predictions. We consider the following approaches:

(A) From the t-channel point of view any two-body hadronic amplitude can be separated into (I) exchange of "ordinary" trajectories and (II) exchange of the Pomeranchuk singularity.

(B) From the s-channel point of view, we have (I) s-channel resonances and (II) nonresonating background. The constraints which result from identifying the corresponding parts of the amplitude within approaches (A) and (B) are well known.[2,5]

(C) The s-channel partial waves which give important contributions to part (I) are mostly the so-called "peripheral" partial waves. They are centered around $l \sim p^*R$, where p^* is the c.m. momentum and R is the "hadronic radius." The important contributions to part (II) come from all partial waves $0 \leq l \leq p^*R$. These statements, when combined with the t-channel picture (A), impose on the ordinary exchanges a condition which is often referred to as the absorption model, namely, the low partial waves do not contribute much to "ordinary" exchanges in inelastic, peripheral collisions. On the other hand, Pomeranchukon exchange is associated with diffraction scattering and is accounted for by strong absorption in all waves with $l \leq p^*R$. The consistency between descriptions (B) and (C) requires that the important s-channel resonances lie on $l \sim \sqrt{s}$ curves in a Chew-Frautschi plot.

(D) Assuming that hadrons are made out of quarks, hadronic amplitudes may involve (I) the annihilation of a $q\bar{q}$ pair and the creation of another pair; (II) "elastic" qq and $q\bar{q}$ scattering. This picture is related to our descriptions (A) and (B) by the duality diagrams[6] [Fig. 1(a)] in which ordinary t-channel exchanges as well as s-channel resonances are viewed as annihilations and creations of $q\bar{q}$ pairs. In Pomeranchukon-exchange amplitudes no quarks are exchanged between the participating hadrons [Fig. 1(b)]. The consistency of descriptions (D) and (C) implies that the three quarks in a baryon are "located" in some sense on the baryon "surface" since the partial waves with $l \sim p^*R$ are responsible for the $q\bar{q}$ annihilations. The Pomeranchukon's contribution to the total hadronic cross section is viewed in this picture as the creation of $q\bar{q}$ pairs within one of the colliding hadrons ($0 \leq l \leq p^*R$), induced by the other hadron without ex-

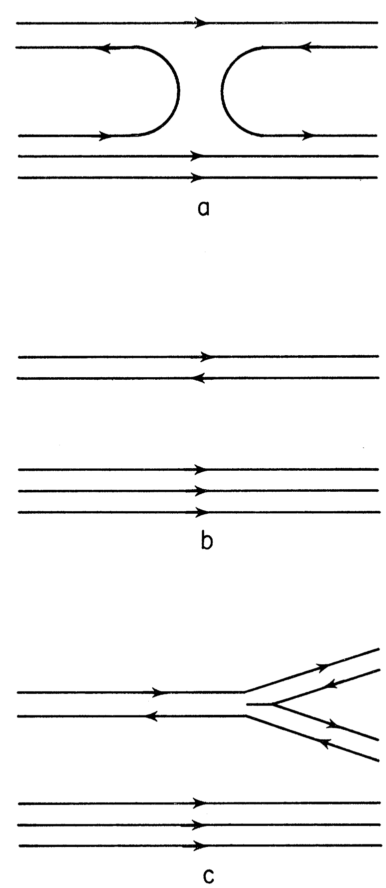

FIG. 1. (a) Duality diagram for an s-channel resonance or a t-channel ordinary exchange. (b) The corresponding diagram for Pomeranchukon exchange in elastic scattering. (c) A typical contribution of the Pomeranchukon to a total meson-baryon cross section.

changing any quarks. The produced pairs are then emitted as mesons [Fig. 1(c)].

(E) In case that one of the colliding particles is a virtual photon, we may study the q^2 (photon mass) dependence of the amplitude. Again, we expect two parts: (I) resonance excitations, (II) diffractive contributions. The consistency of (E) and (C) requires that in resonance excitations the full size of the hadron is "seen" by the photon, since the interaction is peripheral. The q^2 behavior should represent a typical form factor of an extended object with radius R. The consistency of (E) with (A), (B), and (D) requires that all "ordinary" exchanges and resonance excitations must have such a q^2 dependence and that this part of the amplitude is contributed by the coupling of the photon to one of the three quarks of the hadron [Figs. 2(a) and 2(b)]. The diffractive part of the amplitude involves the induced creation of $q\bar{q}$ pairs in the hadron, without a direct coupling of the photon to any of the three "original" quarks [Fig. 2(c)]. The q^2 dependence of this term may be different from that of part (I).

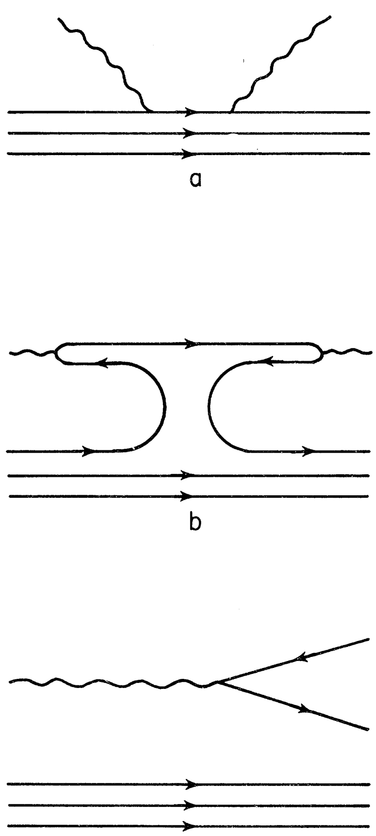

FIG. 2. (a) A quark-model description of an s-channel resonance in Compton scattering. (b) A duality diagram for the same resonance excitation as well as for ordinary exchanges in Compton scattering. (c) A typical contribution of the Pomeranchukon to a total photoabsorption cross section.

(F) According to the parton model[3,4] the electron "sees" the hadron in their common c.m. infinite-momentum frame as a collection of point charges. These charges may be[3] the three quarks and the "sea" of $q\bar{q}$ pairs mentioned above. The amplitude consists of two parts: (I) the contribution of the three quarks, (II) the contribution of the $q\bar{q}$ pairs. Consistency with description (A) demands that the contribution of the $q\bar{q}$ "sea" be associated with the Pomeranchukon exchange since both are indifferent to the hadron charge and strangeness. The constancy of the Pomeranchukon contribution to the total cross section requires an infinite number of $q\bar{q}$ pairs.[3] The consistency of the parton picture (F) with our "conventional" quark descriptions (D) and (E) is presumably given by a Lorentz transformation. The possibility of a photon-induced production of $q\bar{q}$ pairs in the hadron in one frame [as described in (E)] is translated into the interaction of the photon with an infinite sea of such pairs in a different Lorentz frame (as viewed in the parton model). It is only in the latter frame, however, that the electron-quark interaction is instantaneous and that we can view the quarks as point charges.

So far we have only demonstrated that six different simple pictures of high-energy hadronic amplitudes are consistent with each other and are capable of imposing constraints on each other. We shall now assume that the combined picture emerging from these descriptions is indeed approximately true, and proceed to derive its predictions for electron and neutrino scattering.

First we give a brief summary of relevant kinematics.[7] The cross section for $e+p\to e+$ hadrons, integrated over all hadronic final states, is characterized by the two inelastic structure functions W_1 and W_2:

$$\frac{d^2\sigma}{d\Omega dE'}=\frac{4\alpha^2E'^2}{q^4}[\cos^2(\tfrac{1}{2}\theta)W_2(q^2,\nu)+2\sin^2(\tfrac{1}{2}\theta)W_1(q^2,\nu)]. \tag{1}$$

E, E', and θ are, respectively, the initial and final energy and the scattering angle of the electron in the laboratory; q^2 and ν are, respectively, the squared mass and laboratory energy of the exchanged virtual photon. W_1 and W_2 are related to the total photoabsorption cross section σ_T and σ_S for transverse and longitudinal polarizations:

$$W_1(q^2, \nu) \propto \left(\nu - \frac{q^2}{2M}\right)\sigma_T(q^2, \nu), \tag{2}$$

$$W_2(q^2, \nu) \propto \left(\nu - \frac{q^2}{2M}\right)\frac{q^2}{q^2+\nu^2}[\sigma_T(q^2, \nu), + \sigma_S(q^2, \nu)]. \tag{3}$$

In the analogous processes $\nu(\bar{\nu}) + p \to l^-(l^+) +$ hadrons, the kinematics is similar.[8] However, a third function $W_3(q^2, \nu)$ appears in the expression analogous to (1). Three total cross sections can be defined[8] for the absorption of the weak current by the proton: σ_S (for longitudinal polarization) and σ_L and σ_R (for left-handed and right-handed transverse polarizations). $W_1(q^2, \nu)$ and $W_2(q^2, \nu)$ are, again, expressed by relations (2) and (3) with σ_T replaced by $\frac{1}{2}(\sigma_L + \sigma_R)$. $W_3(q^2, \nu)$ is proportional to $\sigma_R - \sigma_L$.

Since our model includes both the Pomeranchukon-dominance assumption and a specific version of the parton model, its predictions include the familiar predictions of both models as well as additional predictions which are specific to the present model. The entire list of predictions includes the following:

(1) $\sigma_T(q^2, \nu)$ and $\sigma_S(q^2, \nu)$ should be constant in ν at large ν and q^2. The deviations from a constant cross section should decrease rapidly[1] with q^2. Consequently, νW_2 and $\nu^{-1}W_1$ should be constant in ν at large ν and q^2. The ratio σ_S/σ_T should also be constant. Experimentally, νW_2 is approximately constant[9] in ν but the possibility of a fall-off at large ν definitely exists. At small q^2, where this falloff is observed,[9] it is not unexpected. At larger q^2 no indications for such an effect exist at present.[9] The ratio σ_S/σ_T appears to be constant in ν.[9]

(2) At large q^2 the ep and en cross sections should be equal even at moderate energies.[1] The region $q^2 \sim 2$-3 BeV^2, $\nu \sim 5$-10 BeV should be appropriate for testing this.

(3) In neutrino scattering, $W_3(q^2, \nu)$ should vanish for large q^2 and ν. Consequently, $\sigma_L(q^2, \nu) = \sigma_R(q^2, \nu)$. This follows from the $C = +1$ property of the Pomeranchukon which prevents it from coupling to a vector ($C = -1$) and an axial ($C = +1$) current.

(4) At large q^2 and ν, neutrino and antineutrino cross sections on any hadronic target should be the same. This follows from the equal couplings of the Pomeranchukon to the $I_3 = \pm 1$ components of the weak current.

(5) The q^2 dependence of the amplitude for specific inelastic channels should be different for diffractive and nondiffractive processes. For instance, the q^2 dependence of $d\sigma(e^- + p \to e^- + \rho^0 + p)/dt$ at large ν and small t is predicted to be similar to that of $\sigma_T(q^2, \nu)$, while $d\sigma(e^- + p \to e^- + \pi^+ + n)/dt$ should vary with q^2 like, say, the elastic nucleon form factors. Such experiments are feasible in the immediate future and we urge the experimentalists to embark on a detailed program of studying such specific inelastic channels.

(6) Current-algebra sum rules such as the Adler sum rule should be violated.[1] The sum rule of Gross and Llewellyn Smith[10] deals with a certain average of the baryon number and hypercharge of the relevant "partons." It reads:

$$\frac{q^2}{M}\int \frac{d\nu}{\nu} W_3(q^2, \nu) = 4\langle B\rangle + 2\langle Y\rangle. \tag{4}$$

In our model this is obeyed in a trivial way since we have $W_3 = 0$ and the average baryon number and hypercharge of the infinite sea is zero. In general, our model disconnects the scattering in the deep inelastic region from the specific identity of the hadron as exhibited by its three quarks. The "infinite sea" (and the Pomeranchukon) is indifferent to the charge or strangeness of the hadron and therefore teaches us nothing about those hadron properties which depend on its charge or strangeness.

(7) Assuming that the quarks or partons have spin $\frac{1}{2}$, we must have[3] $\sigma_S \sim 0$ (in agreement with experiment).[9]

(8) As in any parton model,[3] "scaling" is predicted in our model; namely, $\nu W_2(q^2, \nu)$ and $W_1(q^2, \nu)$ are functions of ν/q^2 only. This is satisfied experimentally.[9] Note that in our picture the contributions of "ordinary" trajectories do not "scale."

(9) The mean-square charge of the infinite sea of $q\bar{q}$ pairs (assuming equal numbers of p, n, and λ quarks) is 2/9. Using the Bjorken-Paschos sum rule[3] we predict, for large q^2,

$$\frac{q^2}{2M}\int \frac{d\nu}{\nu} W_2(q^2, \nu) = 2/9. \tag{5}$$

The experimental value[9] for Eq. (5), assuming that $\sigma_S = 0$ and integrating to $2M\nu/q^2 \sim 20$, is 0.165 (with a 5-10% error). Assuming that νW_2 remains constant to $\nu = \infty$, we get 0.18 (for $\sigma_S = 0$). It is remarkable that all other models[3] tend to predict numbers larger than 2/9 while the experimental number is slightly below 2/9.[11]

(10) Assuming that the quarks or partons in the infinite-momentum frame have $G_A/G_V = 1$, and using conservation of vector current, one gets[8] a sum rule similar to (5) for neutrino reactions. The sum rule together with our predictions $\sigma_S = 0$, $\sigma_L = \sigma_R$ can be translated into a prediction for the absolute magnitude of the total inelastic neutrino cross section.[8] The prediction is $\sigma_{\rm tot} = 0.59E$ (σ in 10^{-38} cm^2/nucleon; E in GeV). The only available experimental number is[12] $\sigma_{\rm tot} = (0.80 \pm 0.20)E$.

Note that predictions (1)-(6) follow from our earlier version of the Pomeranchukon dominance model,[1] (7) and (8) follow from the parton model,[3] while (9) and (10) are new predictions which test the specific combination of the two models which is proposed here.

We consider the overall agreement of our predictions with experiment to be encouraging but certainly not conclusive. Electron-deuteron experiments, specific inelastic electron scattering channels, and neutrino experiments are our main source of hope for testing the model. If the model is wrong it should not be too difficult to destroy it, in view of its large number of predictions.

The author acknowledges fruitful discussions with many colleagues at the Weizmann Institute, Stanford Linear Accelerator Center, and Rockefeller University. Many remarks of J. D. Bjorken and F. J. Gilman have been particularly helpful.

*Research supported in part by the Air Force Office of Scientific Research through the European Office of Aerospace Research, OAR, U. S. Air Force under Contract No. F-61052-68-C-0070.

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