sufficiently close to threshold to determine the fits reliably in this region.[7]

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†Present address.

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Possible evidence for quark substructure from electron-positron colliding-beam experiments*

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By endowing quarks with a size and a small anomalous magnetic moment, it is shown that the rise in the ratio $\sigma(e^+e^- \to \text{all hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$ with center-of-mass energy can be simply explained while leaving the observed scaling phenomenon in deep-inelastic electron scattering intact. Speculations and tests of the model are discussed.

In terms of a general over-all understanding of hadronic phenomena, the quark model of "elementary" particles has proven to be remarkably successful.[1] Particle spectra and decay rates, total cross sections, mass differences, and magnetic moments are all in general quantitative agreement with experiment. Furthermore, being the structureless constituents of hadrons, quarks are natural candidates for partons and thus can automatically explain the scaling phenomena observed in deep-inelastic electron scattering.[2] The salient quantitative features of these data (including the most recent neutrino experiments) can be simply understood in terms of this model.[2,3] That such a model can be so successful does indeed seem diabolical in view of the fact that while quarks appear to behave as if they are light quasifree particles, they have never been seen. Obviously, before the model can be completely accepted, this paradoxical behavior must be understood. Various qualitative explanations for this difficulty have been proposed from time to time, but none are very satisfactory and it has become acceptable to ignore them when performing calculations.[1,2]

Because of the rather imprecise nature of the physical quark model and the unique features of very massive virtual-photon processes, several authors have attempted to put the results of the quark-parton model onto a firmer basis by using so-called light-cone algebra techniques.[2,4] These have the advantage of avoiding a specification of the hadronic states involved in the process (and thus possibly the problem of free quarks) and concentrate upon the properties of operators. Naturally, the great predictive power of the more naive models is thereby sacrificed in favor of a greater generality and, one hopes, a sounder footing. An important prediction of the quark-parton model that can be put onto a firmer basis is that the total asymptotic cross section for electron-positron colliding beams making hadrons via one-photon exchange should behave like the total cross section for Bhabha scattering.[4] In other words, the ratio

$$R_{e^+e^-}(s) \equiv \frac{\sigma(e^+e^- \to \text{all hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} \qquad (1)$$

should become a constant independent of s (the square of the center-of-mass energy) approaching the value $\sum_i Q_i^2$, where Q_i is the charge of the ith kind of quark. In the original quark model[1] $\sum_i Q_i^2 = \frac{2}{3}$; however, in the more popular colored quark model[4] (needed to explain the $\pi^0 \to 2\gamma$ decay), $\sum_i Q_i^2 = 2$. The constancy of $R_{e^+e^-}$ is equivalent to the scaling phenomenon seen in deep-inelastic electron scattering and is most simply derived by assuming that the virtual photon creates quark-antiquark pairs which eventually decay into hadrons. Unfortunately, data from the Cambridge Electron Accelerator published a few months ago[5] indicate that $R_{e^+e^-}(s)$ is rising roughly linearly with s from a value of ~2 at $s \sim 4$ GeV^2 to a value of ~6 at $s \sim 30$ GeV^2. These data have recently been confirmed by an independent Stanford experiment (SPEAR).[6] Unless the interpretation of these experiments is erroneous (for example, because of an anomalously large two-photon contribution), they surely pose a serious threat to our present formulations of the quark model. It might be argued that the asymptotic region has not yet been reached in these experiments. However, this seems somewhat unreasonable in view of the fact that scaling is observed at quite low values of momentum transferred squared (q^2) in the deep-inelastic region (~1 GeV^2) whereas $R_{e^+e^-}(s)$ is still rising at $s \sim 30$ GeV^2. Naively, one would not expect scaling to set in at such vastly differing values of s and q^2 (e.g., two orders of magnitude). Obviously one would like to find a mechanism which preserves all of the previous quark-model results (including the *observed* deep-inelastic scaling phenomenon) and yet gives a rising $R_{e^+e^-}(s)$. It is the claim of the present paper that such a mechanism can, in fact, be provided by endowing the quarks themselves with structure. Although such an idea may seem somewhat premature (especially in light of the fact that quarks have never been seen) we would like to suggest that it has a certain naturalness and is, in fact, rather conservative. The idea of quark structure has in fact already been proposed by Chanowitz and Drell[7] (some of whose results we shall use below) and is roughly as follows: Since quarks must bind together (albeit "lightly") to form hadrons, there must exist interactions between them mediated, for example, by a massive vector gluon which should renormalize the fundamental quark vertices and change the conventional structureless quark electromagnetic vertex $Q\gamma_\mu$ to the form

$$Q\left[F_1(q^2)\gamma_\mu + i\sigma_{\mu\nu}q^\nu \frac{\kappa_Q}{2M_Q}F_2(q^2)\right]. \qquad (2)$$

The quark thus acquires an anomalous magnetic moment κ_Q (measured in units of quark magnetons $e/2M_Q$, where M_Q is the quark mass) and a size characterized by the form factors $F_i(q^2)$. This, of course, happens in traditional theories, and even in quantum electrodynamics the "elementary" electron acquires an anomalous magnetic moment and a size characterized by its mass and the fine-structure constant, α.

Our main result will be to show that the modification of the vertex due to Eq. (2) causes $R_{e^+e^-}(s)$ to rise rapidly with s before eventually falling. However, in the deep-inelastic region any breakdown of scaling implicit in (2) tends to be dampened due to a fortuitous cancellation between the size effect and the effect of κ_Q. As indicated below, it is not difficult to choose parameters which give excellent agreement with the data.

Before discussing further consequences of this result, let us indicate how it comes about. For large s it is not difficult to show that

$$R_{e^+e^-}(s) = \sum_i Q_i^2 \left(|F_1 + \kappa F_2|^2 + \frac{2M_Q^2}{s}\left|F_1 + \frac{s\kappa_Q}{4M_Q^2}F_2\right|^2\right). \qquad (3)$$

To describe the deep-inelastic region we use the conventional structure functions[2] $F_i(q^2, x)$, where $x = -q^2/2M\nu$, M being the nucleon mass and ν the electron energy loss. Assuming that the nucleon wave function is spin-independent, we find asymptotically that

$$F_1(q^2, x) = \sum_i Q_i^2 F_1^2 \mathfrak{F}_1(x) \qquad (4)$$

and

$$F_2(q^2, x) = \sum_i Q_i^2 \left(F_1^2 - \frac{q^2\kappa_Q^2}{4M_Q^2}F_2^2\right)\mathfrak{F}_2(x), \qquad (5)$$

where the $\mathfrak{F}_i(x)$ are the scaling functions which would be derived in the structureless case[2] and the summation is over all the quarks constituting the nucleon. As a consequence of the spin-$\frac{1}{2}$ nature of quarks, $\mathfrak{F}_2(x) = 2x\mathfrak{F}_1(x)$ corresponds to a vanishing of the longitudinal cross section, σ_L, compared with the transverse one, σ_T (i.e., $\sigma_L/\sigma_T = 0$). In order to get an idea of the effects implicit in Eqs. (3)–(5), we make the simplifying assumption that all quarks have the same mass and structure and that $F_1(q^2) = F_2(q^2) \equiv F_Q(q^2)$ [i.e., SU(3) is unbroken]. Suppose further that we are in a region where $|q^2| \ll \Lambda^2$. Then, following CD, we can approximate $F_Q(q^2)$ by $(1 - q^2/\Lambda^2)$. In terms of Λ, the conventional mean square radius of the quark is $\langle r_Q^2\rangle = 6/\Lambda^2$. In this region we can thus write

$$R_{e^+e^-}(s) \simeq \left(\sum_i Q_i^2\right)[(1+3\kappa_Q+\kappa_Q^2)+(\tfrac{1}{3}\langle r_Q^2\rangle+\tfrac{1}{2}\mu_Q^2)s] \tag{6}$$

and

$$R_2(q^2) \equiv \frac{F_2(q^2,x)}{\sum_i Q_i^2 \mathfrak{F}_2(x)} \simeq 1+(\tfrac{1}{3}\langle r_Q^2\rangle - \mu_Q^2)q^2, \tag{7}$$

where $\mu_Q \equiv \kappa_Q/2M_Q$. These make quite clear the different ways the effects enter in the two expressions: They add in $R_{e^+e^-}$ (leading to an initial linear rise with s), whereas they tend to cancel in R_2. Taking these expressions at face value and demanding that there be no deviation from scaling leads to the estimate $\Lambda^2 \sim 40$ GeV^2 (using $\sum_i Q_i^2 = 2$). Such a relatively small value for Λ means that one cannot justify the small-q^2 expansion of $F_Q(q^2)$ used in Eqs. (6) and (7), and one is forced to choose a form which has a more realistic large-q^2 behavior. A convenient parametrization for $F_Q(q^2)$ is provided by the pole form $(1-q^2/\Lambda^2)^{-1}$, suggested by CD, and we have used this (together with $\sum_i Q_i^2 = 2$) to fit the data.[8] Some typical fits are shown in Fig. 1. Roughly speaking, the data[5] constrain $\Lambda \simeq 8-10$ GeV and $\mu_Q \simeq 0.1 \rightarrow 0.2$ GeV^{-1}. In Fig. 2, we have plotted the corresponding deviations from scaling predicted by these fits. It is clear that in the region thus far explored experimentally[3] ($|q^2| \lesssim 15$ GeV/c^2), such deviations are too small to have been detected. Note, further, that it is clearly quite possible to have a good fit to $R_{e^+e^-}$ *and yet constrain* $R_2(q^2)$ *to be* $\lesssim 5\%$, *even up to* $|q^2| \simeq 50$ GeV/c^2. In other words, it is possible for quark structure effects to dominate the e^+e^- experiments and yet be essentially undetectable in the deep-inelastic region until very large values of $|q^2|$ are reached. Note that the combined data clearly cannot be satisfied either by introducing only an anomalous quark magnetic moment without form factors or vice versa (as attempted by CD[7]). Since a small change in the parameters Λ and μ_Q produces a significant change in both $R_{e^+e^-}$ and R_2 (particularly the latter) accurate data can provide a stringent test for this model.

A word of caution concerning deviations from scaling is worth making here. As is well known,[3] at low $|q^2|$, effects due to the *approach* to scaling could mask (or imitate) effects due to a true breakdown in scaling. Thus, for instance, what may be seen as a small deviation from scaling could simply be due to a term such as $(M_Q^2/q^2)G_i(x)$ in $F_i(x)$ which has not yet become negligible; at large values of q^2 (e.g., 30 GeV/c^2), one certainly expects such terms to become quite unimportant. However, some care must be exercised here because the breaking of scaling due to κ_Q grows like q^2 (or s), leading, for instance, to a possible additional term such as $-\frac{1}{4}\kappa_Q^2 F_Q^2(q^2)G_2(x)$ in $R_2(q^2)$. The smallness of κ_Q^2 ($\lesssim 0.01$, see below) ensures that this term is negligible provided the approach to scaling is rapid [i.e., the scale is set by a mass such as $M_Q < 1$ GeV and $G_i(x) \sim F_i(x)$]. A similar remark can be made concerning additional terms in $R_{e^+e^-}(s)$ and $R_1(q^2)$.

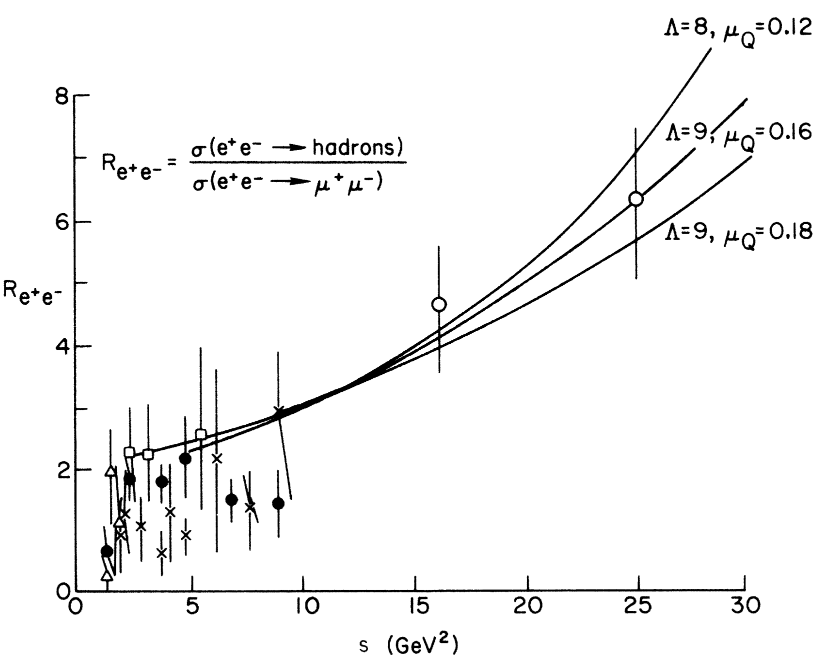

FIG. 1. $R_{e^+e^-}$ versus s for various values of Λ (in GeV^2) and μ_Q (in GeV^{-1}); the data are taken from Refs. 5 and 6.

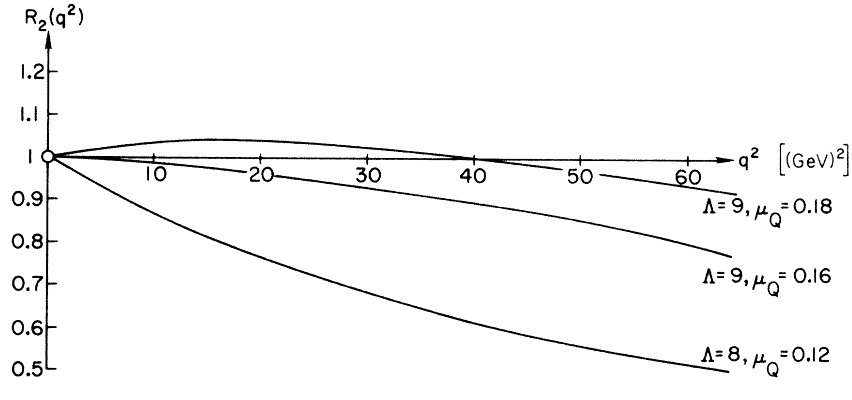

FIG. 2. R_2 versus q^2 for the values of Λ and μ_Q shown in Fig. 1, illustrating the corresponding deviations from scaling expected in the deep-inelastic region.

The smallness of κ_Q alluded to above can be estimated from the small-s (<10 GeV^2) behavior of $R_{e^+e^-}$, which should "extrapolate" back to $2(1+3\kappa_Q+\kappa_Q^2)$. The large scatter of points from different experiments in this region[5,6] (see Fig. 1) does not allow a precise determination of κ_Q in this way; one hopes this can be done when these various data settle down. In any case, even the present data restrict $|\kappa_Q| \lesssim 0.15$ with a suggestion that it is in fact negative. If one insists that it is positive, then it is $\lesssim 0.05$. This small value of κ_Q is nicely consistent with the original quark model [based upon SU(6)] which predicts that the magnetic moment of the proton (μ_p) should be the same as that of the quark,[1] i.e., $2.79/2M \simeq (1+\kappa_Q)/2M_Q$ (recall that it also predicts that the neutron moment $\mu_n = -\frac{2}{3}\mu_p$, in good agreement with experiment). From our fits to $R_{e^+e^-}$ we saw that $|\kappa_Q/2M_Q| \simeq 0.15$, so $M_Q/M \simeq (2.79 \pm 0.30)^{-1}$, the + sign going with a negative κ_Q and vice versa. It is intriguing to note that a negative κ_Q makes M_Q become even closer to $M/3$ (~310 MeV) than in the old model. If $\kappa_Q > 0$, then the above leads to $M_Q \simeq 0.4M \simeq 375$ MeV. Either of these values for M_Q leads to a value of $|\kappa_Q| \simeq 0.1$, showing a nice over-all consistency between the data and the simple model.

We have not, as yet, said anything about $F_1(q^2, x)$. From Eq. (4) we see that, in contrast with $F_2(q^2, x)$ and $R_{e^+e^-}(s)$, it does not contain an explicit q^2 in the numerator, so its deviation from scaling is dominated entirely by $F_Q^2(q^2)$. Hence, one would expect to see larger deviations from scaling in $F_1(q^2, x)$ than in $F_2(q^2, x)$, especially at large $|q^2|$. There is already a hint of this in an analysis recently presented by Bodek.[3] A more conventional way to compare F_1 and F_2 is to use the ratio σ_L/σ_T, which vanishes in the structureless quark-parton model. Here, however, we find

$$\frac{\sigma_L}{\sigma_T} \to \mu_Q^2(4x^2M^2 - q^2) \tag{8}$$

independent of $F_Q^2(q^2)$. Again we have dropped terms which depend upon the approach to scaling since they are $O(\kappa_Q^2)$. Note, however, that in the small-$|q^2|$ region *both* terms in Eq. (8) are small and comparable to those neglected, so the expression cannot be justified until $|q^2|$ exceeds ~10 (GeV/c)^2, where the first term begins to become significant. Equation (8) appears to be consistent with the present data.[2,3] Its most striking aspect is its prediction that σ_L/σ_T should eventually rise like $-q^2\kappa_Q^2/4M_Q^2$ so that, for instance, at $q^2 = -20$ GeV/c^2, we might expect σ_L/σ_T to be as high as 0.4. Such an effect should be easily detectable and will provide the most crucial test of the model.

Finally, we examine the question as to whether the values for Λ and μ_Q required to fit the data are in any sense "reasonable." In the quark-parton model the electromagnetic properties of the nucleon are carried entirely by the quarks; thus it is generally assumed that they are bound by a neutral vector meson ("gluon") ($gB^\mu\bar{\psi}\gamma_\mu\psi$). Our fits require the quark to have the conventional small mass (~350 MeV), and this is sometimes qualitatively explained by introducing a scalar interaction ($\sigma\bar{\psi}\psi$) which reduces the presumed large mass of a free quark to its "observed" effective small mass (M_Q). It seems most unlikely that the gluon mass (M_G) is less than M_Q, so it is reasonable to suppose that $M_G \gg M_Q$. In that case, one might guess that $\kappa_Q \sim M_Q^2/\tilde{M}_G^2$ and $\Lambda^2 \sim \tilde{M}_G^2$, where $\tilde{M}_G$ is some *effective* gluon mass (*not* necessarily M_G). Hence, one expects $\kappa_Q \sim O(M_Q^2/\Lambda^2)$, which would certainly make κ_Q small, though considerably smaller than our fit. Since $M_Q^2/M_G^2 \ll 1$ (M_G the real gluon mass), one might hope to make a perturbation expansion for κ_Q in terms of a small parameter such as $g^2(M_Q^2/M_G^2)$ and for $F_Q(q^2)$ in terms of g^2q^2/M_G^2 (for $q^2 \ll M_G^2/g^2$). As a first attempt along these lines, one can consider ladder graphs for the electromagnetic vertex. For instance, the first-order correction (i.e., a single gluon exchange which was considered by CD) leads to $\kappa_Q = (g^2/3\pi^2)(M_Q^2/M_G^2)$ and $\Lambda^2 = 48\pi^2 M_G^2/g^2 \ln(M_G^2/-q^2)$, where $M_Q^2 \ll -q^2 \ll M_G^2$. Together these would imply that $\mu_Q^2/\Lambda^2 \simeq \frac{1}{4}\kappa_Q$, which, as an order-of-magnitude estimate, is not inconsistent with our fits. On the other hand, it is difficult to see how a negative κ_Q (which is mildly favored by the data) can emerge from such a model. Obviously, any realistic estimate of these internal properties of the quarks must be derived from a more realistic model which takes into account some of their more peculiar properties. Finally, it is worth pointing out that a fit to the structure function $F_2(x)$ based upon a quark-parton model requires two masses, one small (a few hundred MeV, to be associated with the quark) and the other large (several GeV, to be associated with the nuclear wave function).[9]

I would like to thank my various colleagues for conversations on these matters, particularly Mike Chanowitz and Bill Bardeen.

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[1]See, e.g., J. J. J. Kokkedee, *The Quark Model* (Benjamin, New York, 1969).

[2]See, e.g., R. P. Feynman, *Photon-Hadron Interactions* (Benjamin, New York, 1972).

[3]E. D. Bloom, talk presented to the International Symposium on Electron and Photon Interactions at High Energies, Bonn, 1973 [SLAC Report No. SLAC-PUB-1319, 1973 (unpublished)]; A. Bodek, talk presented to the APS meeting, Berkeley, 1973 [SLAC Report No. SLAC-PUB-1327, 1973 (unpublished)].

[4]See, e.g., H. Fritzsch and M. Gell-Mann, in *Proceedings of the XVI International Conference on High Energy Physics, Chicago-Batavia, Ill., 1972,* edited by J. D. Jackson and A. Roberts (NAL, Batavia, Ill., 1973), Vol. 2, p. 135.

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[7]M. Chanowitz and S. D. Drell, Phys. Rev. Lett. 30, 807 (1973); Phys. Rev. D 9, 2078 (1974), hereafter referred to as CD.

[8]We should emphasize that such a form in no way is meant to imply that a particle of mass Λ is supposed to exist; this pole is simply a convenient parametrization for $|q^2| < \Lambda^2$.

[9]G. B. West, Phys. Rev. Lett. 31, 798 (1973).