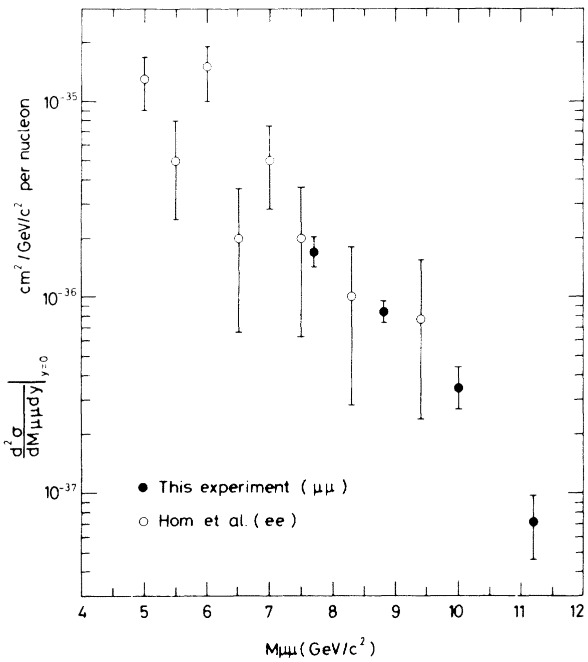

FIG. 3. Comparison of this experiment with results of Hom *et al.* (Ref. 13).

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When is the Deuteron Six Quarks?—Possible Evidence Against Dimensional Scaling*

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Recent data on high-energy elastic and threshold inelastic electron scattering are shown to provide a sensitive test of the constituent nature of the target. Present evidence seems to support a quark description at these energies but mitigates against a naive dimensional-scaling argument.

Recently, a series of experiments exploring both the elastic and threshold inelastic behavior of electron scattering from deuterium at large momentum transfers (Q) have been reported.[1] One of the aims of this Letter is to exploit the theoretical connection between them[2-4] in an attempt to determine whether the deuteron is behaving more quarklike than nucleonlike at these values of Q^2. Below I shall propose a quantitative test that is independent of the detailed underlying dynamics and requires only measured data as input.

The elastic data have been analyzed[1] both in terms of conventional nuclear physics, using essentially nonrelativistic potential models,[5] and in terms of the quark-parton model using dimensional-scaling arguments.[6] Both have been found to give an adequate description, although each is subject to serious criticism. A somewhat different analysis which de-emphasizes the detailed internal dynamics was recently suggested by the author.[3] Unfortunately, at that time the existing data on the inelastic structure function[7] $F_2(Q^2, \omega)$ were inadequate because the smallest measured value of ω was relatively large (~3) compared to the threshold value of 1. Nevertheless an adequate description was found that worked up to surprisingly large values of ω, indicating that the coherent nature of the target was persisting well into the region where an incoherent description would have been expected to work better. In this Letter, I shall show that the new data are in very good agreement with the threshold relationship but in such a way that it appears to be in disagreement with the predictions of dimensional scaling. On the other hand, there is some evidence that it does appear to favor a quark description over a nucleon one. I shall elaborate on this further below. First, however, let us review briefly how the relationship between the elastic and inelastic structure functions arises.

There are basically two ways of "deriving" the relationship[2]—one kinematic (Bloom-Gilman duality) and the other dynamic (Drell-Yan-West). I first concentrate on a variant of the former since this will help focus attention on the phenomenology. The idea is that the asymptotic Q^2 behavior of $F_2(Q^2, \omega)$ as it approaches threshold (i.e., $\omega \to 1$) should join smoothly onto that of its elastic counterpart $A(Q^2)$ at $\omega = 1$. Since F_2 depends on both ω and Q^2 this requires an averaging procedure over a range of ω near $\omega = 1$. Thus, for large Q^2, I write

$$\int_1^{1+2M_DB/Q^2} d\omega\, F_2(Q^2, \omega) = A(Q^2), \qquad (1)$$

where B is a measure of energy region over which the averaging is performed. Clearly this must correspond at least to the elastic peak, in which case B can be identified with the deuteron binding energy ($\simeq 2.2$ MeV). For the experiment considered,[1] however, the energy resolution is considerably greater than this (20–30 MeV), so in comparing Eq. (1) with data, B must take on a value of at least roughly this magnitude (i.e., ~25 MeV). It was pointed out in Ref. 3 that one cannot naively take the large-Q^2 limit of Eq. (1) and replace $F_2(Q^2, \omega)$ by its assumed scaling limit $F_2(\omega)$ since, in general, the remainder terms, when integrated, can contribute at least as much as the leading ones. Indeed, I emphasized that this was basically the reason that in the nucleon case, the vanishing of σ_L/σ_T is *not* a necessary consequence of the fact that it vanishes for the purely elastic part. Thus, for example, for a scalar target where $\sigma_L/\sigma_T \to \infty$ for the elastic part, it need not do so for the inelastic part even though Eq. (1) remains valid.

By introducing a new variable $\omega' = \omega + M_0^2/Q^2$, I assume that the approach to scaling can be greatly accelerated so that for large Q^2

$$\int_{1+M_0^2/Q^2}^{1+(M_0^2+2M_DB)/Q^2} d\omega'\, F_2(\omega') = A(Q^2). \qquad (2)$$

In Ref. 3, I showed that M_0 is unique. Usually $F_2(\omega')$ is parametrized by a power-law behavior [e.g., $F_2(\omega') = N(\omega'-1)^p$] which leads to

$$\lim_{Q^2\to\infty} A(Q^2) \to \frac{2M_DBN}{M_0^2}\left(\frac{M_0^2}{Q^2}\right)^{p+1}.$$

In Ref. 3, I found that this gave an adequate, though not spectacular, description of the data. With the new data in hand, I have performed a re-analysis and have found that a power-law fit is not very convincing, even for $A(Q^2)$. A much better fit is obtained with an exponential form[8] $A(Q^2) \sim e^{-bQ}$; for example, suppose[9]

$$F_2(\omega') = C[\omega'/(\omega'-1)]^{3/2} \exp[-a/(\omega'-1)^{1/2}],$$

then Eq. (2) leads to $A(Q^2) \to DQe^{-bQ}$, where $C = M_0^3D/2M_DB$ and $a = M_0 b$. In Fig. 1, I have plotted $A(Q^2)/Q$ vs Q, from which it is clear that this form gives a very good fit to the data; I find that $D \simeq 0.33$ GeV^{-1} and $b \simeq 8.2$ GeV^{-1}. I have also examined[10] the inelastic data and found that scaling appears to be best when $M_0^2 \simeq 1.3$ (GeV/c)^2. I thus predict $a = M_0 b \simeq 9.35$ and, taking $B \simeq 25$ MeV, $C \simeq 5$. In Fig. 2, I have therefore plotted $F_2(\omega) = 5(1-1/\omega')^{-3/2}\exp[-9.4(\omega'-1)^{-1/2}]$ together with the data. The agreement is remarkably good; furthermore, there is some evidence that the predicted fit imporves as Q^2 gets larger and $\omega' \to 1$, as it should. Unfortunately, of course, the data get worse in this region.

The exponential fit is considerably better than a power-law fit—in particular, better than the Q^{-10} behavior suggested by dimensional scaling.[6] Indeed, even the suggested modified form[1] $A(Q^2) = G_E^4(Q^2/4)(1+Q^2/m^2)^{-1}$ [where $G_E(Q^2)$ is the conventional electric nucleon form factor and $m^2 \simeq 0.28$ (GeV/c)^2] is not terribly good, particularly in its normalization for large Q^2. In fact, since the dominant mass scale in this fit is 4×0.71 GeV^2 = 2.8 GeV^2 [recall that the scale in G_E is 0.71 GeV^2] and since the largest reliably measured value of Q^2 is 4 (GeV/c)^2, one clearly could not claim that the data definitely showed a Q^{-10}

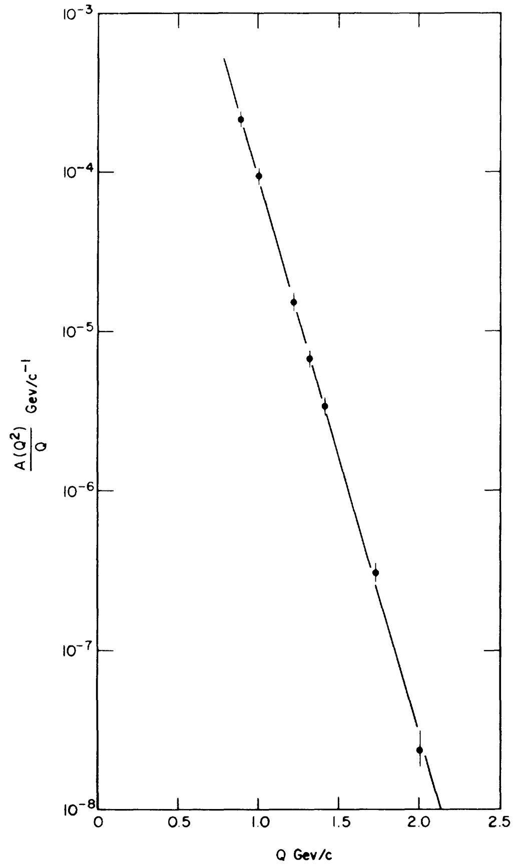

FIG. 1. Plot of $A(Q^2)/Q$ vs Q; the straight line fit is $A(Q^2)/Q = 0.33e^{-8.2Q}$.

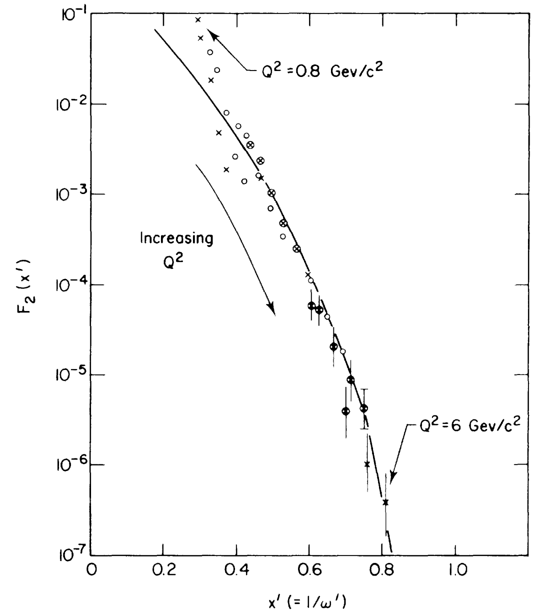

FIG. 2. Plot of $F_2(\omega')$ vs x' ($= 1/\omega'$) for value of Q^2 ranging from 0.8 to 6 GeV/c^2; the fit $F_2(\omega') = 5(1-1/\omega')^{-3/2}\exp[-9.4(\omega'-1)^{-1/2}]$ is derived from the parameters of Fig. 1.

behavior even if the fit were better. The normalization problem of this fit shows up in a particularly startling fashion in the plot of $\rho(\epsilon, \mathbf{Q}^2) \equiv W_2(\epsilon, Q^2)/A(Q^2)$ vs Q^2, where $\epsilon \equiv W - M_D$. In Fig. 5 of Ref. 1 such a plot was constructed using this fit for $A(\mathbf{Q}^2)$ but taking W_2 from data. For $\epsilon = 0$, for example, it was found that $\rho \sim 0.8$ independent of Q^2; taking $A(Q^2)$ from data, one finds instead that $\rho \sim 40$. On the other hand, with my fits, I find that for $\epsilon = 0$, $\rho \simeq 1/B \simeq 40$, in excellent agreement with the data. I therefore conclude that the evidence in favor of the dimensional-scaling arguments is not very convincing. This, of course, does *not* mean that the deuteron is not behaving like six quarks in these experiments; rather, it suggests that the neglect of the dynamical role of the wave function is too naive. In a certain sense, the dimensional-scaling arguments can be thought of as analogous to a zero-range approximation in that only the free propagator form of the internal constituents is kept. My analysis suggests that, at least in this range of $\mathbf{Q}^2$, true coherent bound-state effects remain important.

To decide whether the deuteron is behaving more like a bound state of six quarks than one of two nucleons is a much more subtle question. A dynamical derivation of the connection between $F_2(\omega \to 1)$ and $A(Q^2 \to \infty)$ can be obtained in an identical way for the deuteron as it was obtained for the nucleon.[4] Basically, a connection exists because both regions are sensitive to the large-internal-momentum behavior of the struck constituent.[2] The difference between a quark and nuclear description of this connection lies mostly in the fact that the quark is structureless, whereas the nucleon has its own structure functions. Thus, if the deuteron is taken to be a bag of quarks with no reference to nucleons then the connection is essentially the same as for the nucleon and is the one that we have employed above that follows from Eq. (2). On the other hand, if the deuteron consists of two extended nucleons, I can use a result derived in a previous work,[4] viz., that in the scaling limit,

$$\lim_{\omega\to 1} F_2(\omega) \sim \int_{[M/4(\omega-1)]^2}^{\infty} dQ^2 \frac{A(Q^2)}{G_E^2(Q^2)} \int_1^{\omega} F_2^{(N)}(\omega)d\omega, \qquad (3)$$

where $F_2^{(N)}(\omega)$ is the sum of proton and neutron structure functions. Suppose that we have power-law behavior, i.e., $A(Q^2) \to (Q^2)^{-2g}$, $F_2^{(N)}(\omega) \to (\omega-1)^r$, and $G_E(Q^2) \to (Q^2)^{-n}$ (with $2n = r+1$), then Eq. (3) leads to $F_2(\omega) \to (\omega-1)^{2(2g-n-1)}$. This is quite different from the quark description which gave $F_2(\omega) \to (\omega-1)^{2g-1}$. For example, in Ref. 3 I suggested that $2g \simeq 12$ and $n \simeq \frac{5}{2}$; the nuclear description thus gives $F_2(\omega) \to (\omega-1)^{17}$ whereas the quark description gives $F_2(\omega) \to (\omega-1)^{11}$. There is a considerable difference in behavior and this illustrates nicely *how one can determine the effective constituent nature of the deuteron solely from experimental input.* The older data (larger ω values) appear more consistent with $(\omega-1)^{11}$ suggesting that the deuteron is behaving like a bag of quarks. With the fits discussed in this Letter, we have seen that for the quark case $A(Q^2) \sim e^{-bQ}$ leads to $F_2(\omega) \sim \exp[-bM_0/(\omega-1)^{1/2}]$. However, for the nucleon case the same $A(Q^2)$ leads to $F_2(\omega) \sim \exp[-bM/4(\omega-1)]$ suggesting again that the deuteron is behaving more quarklike than nucleonlike. This conjecture is also supported by the following argument: The bound state nature of the system is reflected in the fact that the threshold occurs at $\omega = 1$; after all, if it were two free nucleons, the threshold would occur at $\omega = 2$. Thus, near $\omega = 1$ the dependent variable is $(\omega-1)$. However, if the system retains knowledge that it is made of nucleons, one might expect that near $\omega = 2$ the dependent variable changes to $(\omega-2)$. Thus, a fit to the threshold behavior in terms of $(\omega-1)$ would not extrapolate smoothly beyond the $\omega = 2$ region if a nucleon representation is predominant. The fact that it does supports the view that at these values of Q^2 the system is behaving more like a bag of quarks. One word of caution should be added: Although Q^2 is relatively large here it should be recalled that $Q^2/\nu^2 \cong 4M_D^2/Q^2 > 1$ for all the data considered; in the true scaling regime, this should vanish. Of course, a large part of this problem is presumably removed by introducing the *ad hoc* ω' variable and, in any case, M_D does not, in general, set the scale. Thus we conclude that the present data tentatively indicate a quarklike character in this region of Q^2. It is worth emphasizing, however, if *the deuteron really is behaving like six quarks at large* Q^2, *then there is little reason to believe the values of* F_2^{neutron} *extracted from* F_2^{deuteron} *near threshold, since they rely on the treatment of the deuteron as two nucleons*.[14]

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[8]Recall that this is the *fastest* falloff of a form factor consistent with analyticity. This means that $\exp[-a/(\omega-1)^{1/2}]$ is the *slowest* growth of $F_2(\omega)$ allowed near $\omega = 1$.

[9]The strange factors like Q and $(\omega'-1)^{-3/2}$ are simply inserted in order to allow an analytic evaluation of Eq. (2). They play no crucial role. Note, however, that I have followed the practice traditionally employed in the nucleon case of using a representation for F_2 which remains constant when $\omega \to \infty$ even though I am interested in $\omega = 1$ only.

[10]A thorough investigation of the "best" value of M_D was not performed; indeed, all calculations were performed on our HP45.