“Six-Quark” Component in the Deuteron from a Comparison of Electron and Neutrino/Antineutrino Structure Functions

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We discuss a way to measure the “six-quark” component in the deuteron from a comparison of the structure functions in ep and ed deep-inelastic scattering and the structure in νp and $\bar{\nu} p$ scattering. Such a determination is obtained by looking at the deviation from 1 in the ratio $T = d(x)\bar{u}(x)/u(x)\bar{d}(x)$, where u and d are the quark distributions determined from νp and $\bar{\nu} p$, and $\bar{u}$ and $\bar{d}$ are the effective quark distributions determined from ep and ed by neglect of coherent six-quark effects.

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Our present understanding of hadrons as extended objects containing colored quarks and gluons suggests that a nucleus might not always behave as a collection of nucleons. Even in the loosely bound deuteron there is a few percent probability that the nucleons are separated by a distance less than their radius. In such a situation it seems reasonable that instead of talking of two clusters of three quarks one should speak of a single six-quark system.^{1,2} Of course, if we were to decompose the six-quark system into clusters they could be either color singlet or octet.^{3,4} A specific estimate of about 5% is obtained from models for the deuteron form factor.^{5,6} Boundary-condition models yield about 5% for the difference between 1 and the integrated deuteron wave function squared from 1 fm to infinity.^{7,8}

Although one might consider fitting low-energy reactions and static deuteron properties in order to determine this probability, it seems to us that deep-inelastic scattering (DIS) is the tool likely to provide the least ambiguous answer.⁹ The quark distribution functions in a six-quark system are different from those of a bound proton-neutron system, whose intrinsic quark distributions suffer no polarization correction. One obvious difference is the structure function for $x > 1$ ($x = Q^2/2M_N\nu$ in the usual notation). For the deuteron the kinematically allowed range for x is $0 \leq x \leq 2$. Although taking the momentum of the nucleons in the deuteron into account (the so-called smearing correction) yields structure functions which extend beyond $x = 1$, there will be no typical behavior near $x \simeq 2$ as one would expect from quark counting

rules. The high- Q^2 behavior of the deuteron form factor, however, seems to indicate that quark counting rules work quite well.⁹⁻¹¹ The structure functions near $x \simeq 2$ would definitely show the coherent six-quark effects that we are after,¹² but it is doubtful that reliable results can be achieved experimentally.¹³

For x sufficiently large, say $x > 0.3$, we believe that it is not necessary to worry about the contributions of sea quarks. We then have (assuming isospin symmetry)

$$F_2^{ep}(x)/x = [4u(x) + d(x)]/9, \quad (1)$$

$$F_2^{en}(x)/x = [u(x) + 4d(x)]/9, \quad (2)$$

where $u(x)$ and $d(x)$ are the up- and down-valence-quark distributions in the proton. Following the arguments given above we assume that in addition to the smearing correction, one should add a contribution to $F_2^{ed}(x)$ because of the probability of scattering coherently off six quarks (which are not restricted to be in color singlets),

$$F_2^{ed}(x)/x = (1 - \delta_6) [F_2^{ep}(x)/x + F_2^{en}(x)/x] + \delta_6 [4u^D(x) + d^D(x)]/9. \quad (3)$$

Here $u^D(x) = d^D(x) = n(x)$ are the up- and down-quark distributions in an isosinglet six-quark state (equal because of isospin symmetry); the index s indicates that a smearing correction has been applied.¹⁴ The quantity δ_6 measures the probability that the deuteron behaves like a system of six quarks.

In order to be able to learn something about δ_6

we need to know the quark distributions in Eqs. (1)–(3). The functions $u(x)$ and $d(x)$ may be obtained from νp and $\bar{\nu} p$ scattering. The accuracy with which these functions are extracted, however, is not very high. Perhaps the most accurately known quantity is the ratio $d(x)/u(x)$, which for $x > 0.3$ is obtained as the ratio $F_2^{\nu p}(x)/F_2^{\bar{\nu} p}(x)$. Statistically much more accurate determinations of the quark distributions are usually obtained from ep and ed scattering—but they are not obtained by use of Eqs. (1)–(3). Rather, one customarily uses

$$F_2^{\nu p}(x)/x = [4\tilde{u}(x) + \tilde{d}(x)]/9, \quad (4)$$

$$\tilde{F}_2^{\nu n}(x)/x = [\tilde{u}(x) + 4\tilde{d}(x)]/9, \quad (5)$$

$$F_e^{\nu d}(x)/x = F_2^{\nu p}(x)/x + \tilde{F}_2^{\nu n}(x)/x, \quad (6)$$

where we put $\tilde{u}(x)$, $\tilde{d}(x)$, and $\tilde{F}_2^{\nu n}$ to indicate that these are effective distributions deduced from proton and deuteron data. Equating Eqs. (1) and (4), and Eqs. (3) and (6), and assuming a simple smearing correction¹⁴

$$\begin{aligned} S(x) &= F_2^{\nu p}(x)/F_2^{\nu s}(x) \\ &= \tilde{F}_2^{\nu n}(x)/\tilde{F}_2^{\nu s}(x) \end{aligned} \quad (7)$$

one finds the following expressions for the distribution functions $\tilde{u}$ and $\tilde{d}$, extracted from electron scattering (ep and ed) in terms of the correct distribution functions u and d , extracted from (anti)neutrino scattering (νp and $\bar{\nu} p$):

$$\begin{aligned} \tilde{u}(x) &= u(x) + \delta_6[u(x) + d(x) \\ &\quad - S(x)n(x)]/3, \end{aligned} \quad (8)$$

$$\begin{aligned} \tilde{d}(x) &= d(x) - 4\delta_6[u(x) + d(x) \\ &\quad - S(x)n(x)]/3. \end{aligned} \quad (9)$$

For the parametrization of the distribution functions we use the normalized $[\int_0^1 dx q(x) = 1]$ function

$$q(x; \alpha, \beta) = \frac{\Gamma(\alpha + \beta + 1)}{\Gamma(\alpha)\Gamma(\beta + 1)} x^{\alpha-1} (1-x)^{\beta}. \quad (10)$$

We then have $u(x) = 2q(x; \alpha_u, \beta_u)$, $d(x) = q(x; \alpha_d, \beta_d)$, and $n(x) = 1.5q(x/2; \alpha_6, \beta_6)$.

For the up- and down-quark distributions we have used the functions found from neutrino/antineutrino-hydrogen scattering in Parker *et al.*¹⁵ They are parametrized as $u(x) = 2q(x; 0.53, 2.85)$, and $d(x) = q(x; 0.63, 3.9)$. Quark counting rules, consistent with the Drell-Yan-West relation,^{11,16} indicate that for six quarks the coefficient β_6 in Eq. (10) is equal to $2N_{\text{quarks}} - 3 = 9$. Arguments from Regge theory indicate that the coeffi-

FIG. 1. The up- and down-valence-quark momentum distribution functions $xu(x)$ and $xd(x)$ in the proton, and the nonstrange-quark momentum distribution $xn(x)$ in a six-quark system for various values of the parameters α_6 and β_6 in Eq. (10).

cient α_6 is of order 0.5, just as for the distribution functions in the proton. In Fig. 1 we have plotted the distribution functions $xu(x)$, $xd(x)$, and $xn(x)$. For the last function a number of values of the parameters α_6 and β_6 have been considered in order to check the sensitivity to them. For a 5% six-quark probability ($\delta_6 = 0.05$) the differences between $xu(x)$ and $x\tilde{u}(x)$ and between $xd(x)$ and $x\tilde{d}(x)$ are very small as one may check from Eqs. (8) and (9). To see the effect one would need to determine these functions to very great precision.

A much more useful quantity is the ratio

$$T = \frac{d(x)/u(x)}{\tilde{d}(x)/\tilde{u}(x)}, \quad (11)$$

which has the following features:

(1) For $\delta_6 = 0$ it is 1, irrespective of any corrections which are applied to relate the ed structure function to the ep and en structure functions, like the smearing correction, relativistic effects, shadowing, etc.¹⁴

(2) For $\delta_6 \neq 0$ small changes in the way the above corrections are applied are an order of magnitude smaller than the effects of putting in the “six-quark” contribution itself. This is demonstrated in Fig. 2, where the effect for $n(x) = 1.5q(x/2; 0.5, 9.0)$ including the smearing correction¹⁴ (solid line 1) is compared with the same choice for $n(x)$ without any smearing (dashed line).

(3) The ratio $d(x)/u(x)$ is expected to be much less dependent on Q^2 than the quark distributions themselves.¹⁷

(4) The ratio $d(x)/u(x)$ can be obtained more

FIG. 2. The calculated value for the ratio $T(x)$ [see Eq. (11)] for various choices for $xn(x)$ (solid lines 1-5; see Fig. 1 for parameters). The smearing correction is taken into account. Neglecting this correction for curve 1 gives the dashed line. The dot-dashed line shows how curve 1 is modified if we take $u(x) = 2q(x; 0.5, 3.0)$ and $d(x) = q(x; 0.6, 4.0)$. The dotted line shows the result for a scale change in the deuteron [see Eq. (12)].

accurately from the neutrino data than the quark distributions itself.

(5) Unfortunately, there is a strong dependence on the form of $n(x)$, the nonstrange-quark distribution in a six-quark system. Although the value $\beta_6 = 9$ may be trusted near $x \approx 2$, the effective form for $n(x)$ in the relevant region $0.3 < x < 0.8$ may be better described with slightly different parameters. The effect of various choices for $n(x)$, and also for different forms for $u(x)$ and $d(x)$, are shown in Fig. 2.

Qualitatively we always find an enhancement of T in the region $0.3 < x < 0.7$. For δ_6 equal to 5% this enhancement is (5-20)%. A quantitative determination of δ_6 is not possible because of the sensitivity to the quark distribution functions. The most optimistic point of view is, of course, that a more accurate experimental determination of T may teach us about both the magnitude of the six-quark contribution and about the distribution function $n(x)$. At this stage one is still far from this, as is shown in Fig. 3, where some of the results for T (see Fig. 2) are compared with the experimentally determined ratio.^{15,18}

Recently, it has been conjectured that the difference in structure functions in nuclei as compared to those in the nucleon indicates a change of scale taking place.¹⁹ For the deuteron this means that in the

FIG. 3. The comparison of some calculated values for $T(x)$ (solid lines 1-5 from Fig. 2) with the experimental values from Refs. 18 (triangles) and 15 (dots).

range $0.2 < x < 0.6$ one would have

$$F_2^{qd}(x, \xi Q^2)/x = F_2^{qp}(x, Q^2)/x + F_2^{qn}(x, Q^2)/x, \quad (12)$$

where $\xi = \xi(Q^2)$ is proportional to the change of scale squared with a Q^2 dependence caused by the strong coupling constant. Using $F(x, \xi Q^2) \sim \xi^{0.25-x} F_2(x, Q^2)$ (Ref. 9) we can again find $\tilde{u}$ and $\tilde{d}$ by comparing Eqs. (1), (2), and (12) with Eqs. (4)-(6). The result for T for a rather arbitrarily chosen $\xi = 0.95$ is also shown in Fig. 2. In the region $0.3 < x < 0.7$ such a change of scale has the same qualitative effect on T as a six-quark distribution as discussed by us. At any Q^2 the effect of a change in scale as in Eq. (12) can, of course, be considered as a six-quark contribution as in Eq. (3). Because of the Q^2 dependence of ξ , however, T in this case has a much stronger Q^2 dependence.

Finally we would like to discuss what the effect in the deuteron implies for the "EMC effect," where the structure function F_2^A for some nucleus is compared with F_2^{ed} .²⁰ We have compared F_2^{qd} with the idealized structure function " F_2^{ed} ," which does not contain any six-quark effects, i.e., is given by Eqs. (4)-(6), but with the correct quark distributions u and d instead of the effective ones $\tilde{u}$ and $\tilde{d}$. The ratio F_2^{qd}/F_2^{ed} , which might be called the "deuterium EMC effect," is given in Fig. 4 for a set of reasonable parameters ($\delta_6 = 0.05$, $\alpha_6 = 0.5$, $\beta_6 = 9.0$) and is indeed small. From this we can conclude that the error made in analyzing the EMC effect in heavier nuclei²¹ (in a six-quark model) be-

FIG. 4. The "EMC effect for deuterium" for a six-quark contribution (solid line, parameters for curve 1 in Figs. 1-3) and for a scale change in the deuteron [dotted line, see Eq. (12)].

cause of neglect of the same effect in the deuteron is not larger than a few percent, in agreement with results found by Bodek.²² We have also plotted the effect when F_2^{ed} is given by Eq. (12) and come to the same conclusion. We note that in both cases the deviation from 1 in the ratio F_2^{ed}/F_2^{ed} is about a factor of 6 smaller than the deviation from 1 in the ratio T . This makes T much more suitable to extract the six-quark effects in the deuteron. For this reason we would very much like to have new high-precision neutrino and antineutrino measurements on hydrogen.

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