Nuclear Structure Functions and the Size of Diquarks in Nucleons

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It is suggested that the observed difference between deep-inelastic structure functions from iron and deuterium targets comes about because two of the quarks in a nucleon are tightly bound in a diquark. It suffices for reproducing the data to assume that the diquark radius is enhanced by 10%–45% in a dense nucleus because of the disturbance from the surrounding nucleons. It is suggested how such a change of the diquark scale could be distinguished from the recently proposed change in the scale of the whole nucleon.

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In this Letter I discuss how *diquarks* could be responsible for the effect observed by the European Muon Collaboration (EMC), i.e., the distortion of the deep-inelastic nucleon structure function, $F_2^{lN}(x, Q^2)$, in going from deuteron to heavy nuclear targets.[1,2]

According to the particular diquark model[3] developed by Jändel, Larsson, and myself, a nucleon is mostly in a bound quark-diquark state, with the diquark, $(ud)_0$, being a very small spin-0 pair of a u and a d quark. This diquark, which we believe is strongly kept together by color magnetic forces, dominates the observed Q^2 dependence of the nucleon structure function at $Q^2 \gg 2$ GeV^2 through its electromagnetic form factor. At small Q^2 values ($Q^2 \lesssim 4$ GeV^2, say), there are also traces of other, and rarer, diquark configurations. These are presumably accidental,[3] and come about because a low-Q^2 virtual photon might experience *any* quark pair, bound or not, as one entity. Anyhow, in this work I do not need to consider such details, since the bulk of data on the EMC effect are taken at $Q^2 \gg 2$ GeV^2.

Now I suggest that the dominating $(ud)_0$ diquark is *somewhat bigger* in a nucleon surrounded by dense nuclear matter than in a free nucleon, or in the rather dilute deuterium nucleus. Already in a nucleon, the forces that keep the diquark together are probably disturbed by the presence of the third quark, so that the $(ud)_0$ is not as small as it "could be." Inside a dense nucleus, it is surrounded by additional quarks and diquarks within a distance not much larger than the dimension of its own nucleon, and this would then result in an even bigger $(ud)_0$.

The idea that the EMC effect is the result of a change of scale in the fundamental interaction is not unique to this picture. In the recent models of Close, Roberts, and Ross[4] and Jaffe[4] it is the dimension of the whole nucleon, or six-quark bag, that sets the scale in the reaction.

The effect of a "growing" diquark can be quantified in a remarkably simple way, with the diquark mean square radius, $\langle r_d^2\rangle_A$, inside the nucleus A as the only *a priori* unknown parameter. It appears on the same level as the nucleon radius in the model of Close, Roberts, and Ross,[4] although I will use a simplified numerical approach [Eq. (3)], which gives the final result [Eq. (5)] in a simple closed form.

In our diquark model,[3] the full Q^2 dependence of F_2 at $Q^2 \gg 2$ GeV^2 comes from the $(ud)_0$ form factor, which in addition must scale in $\langle r_d^2\rangle Q^2$, like any other smeared charge distribution. Hence I get for the two target nuclei A_1 and A_2

$$F_2^{lA_1}(x, Q^2) = F_2^{lA_2}(x, kQ^2), \tag{1}$$

where

$$k \equiv \langle r_d^2\rangle_{A_1} / \langle r_d^2\rangle_{A_2}. \tag{2}$$

When testing this crucial relation I do not need to make use of the detailed fits of quark and diquark momentum distributions and diquark form factors achieved in Ref. 3. The result becomes much more transparent with a simple phenomenological parametrization of the data. This also has the advantage that I can investigate the full x region, which we did not do in Ref. 3. There, we restricted the analysis to $x \gtrsim 0.25$, where F_2 falls with Q^2, so that the falloff of the diquark form factor could be studied. At $x < 0.25$, F_2 rises with Q^2, which in our model is understood as the gradual increase of the contribution from the rather low-energetic u and d quarks in the $(ud)_0$ as the diquark is dissolved into its quarks with increasing Q^2. Also this Q^2 dependence, at low x, is naturally governed by the $(ud)_0$ form factor, and hence scales in $\langle r_d^2\rangle Q^2$.

A convenient parametrization of the muon data[5] taken on an iron target is given by

$$\ln F_2^{\mu \mathrm{Fe}} = -\alpha(x) \ln Q^2 + \beta(x), \tag{3}$$

in the interval of relevance for the EMC effect, namely $9 \lesssim Q^2 \lesssim 50\ \mathrm{GeV}^2$. Then for muon-deuterium scattering, Eq. (1) predicts

$$\ln F_2^{\mu \mathrm{D}} = -\alpha(x) \ln(Q^2/k) + \beta(x), \tag{4}$$

where $k > 1$ is now the ratio given in (2) with $A_2 = \mathrm{Fe}$ and $A_1 = \mathrm{D}$. Hence

$$F_2^{\mu \mathrm{Fe}}/F_2^{\mu \mathrm{D}} = k^{-\alpha(x)}. \tag{5}$$

This is my main result, which tells that the EMC effect depends only on the relative increase of the diquark radius and the slope in a plot of $\ln F_2$ vs $\ln Q^2$ as long as the parametrization (3) describes the data accurately. Observe that the effect is Q^2 independent, in spite of the fact that it primarily comes from a Q^2-dependent diquark form factor. When fitting $\alpha(x)$ to the iron data[5] one gets, disregarding experimental uncertainties, $\alpha(x) = -0.16$, -0.07, -0.04, -0.01, 0.04, 0.07, 0.15, 0.32, and 0.36 for, respectively, $x = 0.05$, 0.08, 0.125, 0.175, 0.25, 0.35, 0.45, 0.55, and 0.65. In Fig. 1 I have used these values for drawing smooth curves that illustrate the result from Eq. (5) with a few reasonable k values. For comparison I have also used the electron-deuterium data from SLAC[6] as input

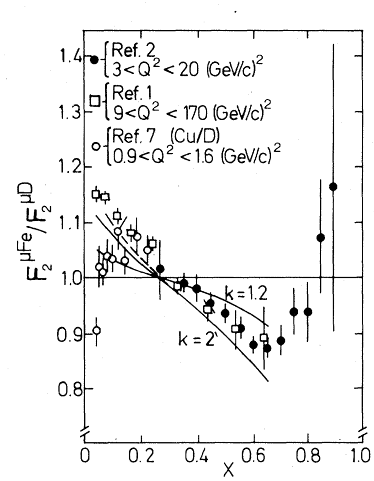

FIG. 1. The ratio of structure functions from iron and deuterium targets as a function of $x = Q^2/2m_p\nu$, where Q^2 is the squared four-momentum transfer and ν is the energy transfer from projectile to target. The data points are taken from Ref. 2 and include data from the CERN EMC (Ref. 1) and from SLAC (Ref. 2). Some data from a copper target (Ref. 7) are also included. The full lines show the expectations from diquark effects with two different values of the parameter k in Eq. (5), and with the EMC data of Ref. 5 used as input. The broken line is the result of using the SLAC data of Ref. 6 as input when $k = 2$.

for the procedure, and then disregarded the fact that Q^2 is not much larger than $2\ \mathrm{GeV}^2$ in all those data. The result is only marginally different from those with CERN data[5] as input in Eq. (3), except for large k values and small x values, as indicated in the figure.

It can be seen that the expected diquark effects are in fair agreement with the data provided the k value is chosen between 1.2 and 2, with a possible preference for the higher value. This corresponds to an increase in the diquark radius of 10%–45% due to the disturbance from the surrounding matter in a dense nucleus. The fit fails at $x > 0.65$, but this is most likely due to the effect of nuclear Fermi motion on the data.

All published models contain one crucial parameter, which is fitted essentially to the slope of the data at intermediate x values in the figure. Examples are the nucleon radius[4] and the percentage of six-quark bags,[8] twelve-quark α-like particles,[9] virtual pions,[10] Δs,[11] and quark-gluon plasmas[12] in a dense nucleus. My model shares the disadvantage with these schemes that it is practically impossible to compute the value of the main parameter from basic theory, such as quantum chromodynamics.

A diquark in iron is disturbed by a few dozen surrounding quarks, if only those in the neighboring nucleons are counted. The total effect depends on the positions, spins, isospins, and colors of those quarks relative to the quarks in the studied diquark. To cause the observed effect, each of the quarks would need to disturb the diquark in such a way that its radius grows by, on the average, 1%–2%. The magnitude of the effect seems quite realistic once it is established that the radius actually *grows* (and does not shrink). Suppose that the forces that confine the quarks inside nucleons can be left out of the problem, so that only residual two-quark forces are responsible for the binding in the diquark and the disturbance from external quarks. I have studied the three-body system of a diquark and an external quark with a few different types of potentials describing the two-quark forces. When the potentials are reduced into one effective potential inside the diquark and one between the diquark and the external quark, it turns out that the diquark actually gets "wider" because of the presence of the external forces, provided that the potentials vanish with growing distance and that there are no external potentials with a stronger binding than the one inside the diquark. Both these requirements seem almost trivially fulfilled. More detailed estimates of the enhancement in the diquark rms radius, however, become extremely sensitive to the exact choice of potentials and of quark and diquark distributions in nucleons.

The following predictions are straightforward in the model:

(1) The effect should gradually disappear at higher Q^2 values (>30 GeV^2, say), where F_2 starts to level off as a function of Q^2.

(2) The effect should be somewhat stronger in heavier nuclei. Although they have almost the same central density as iron, a higher percentage of their nucleons are inside the nucleus and hence disturbed by the environment.

(3) The effect should exist also with a neutrino beam.

(4) When one triggers on an outgoing forward proton, with momentum transfers in the neighborhood of $Q^2 = 10$ GeV$^2/c^2$, the effect at high x values should be enhanced, because protons are produced by directly knocked out diquarks to a much larger extent than hadrons in general. No such sensitivity to the trigger hadron is expected in models where the EMC effect comes from the widening of the whole nucleon. In diquark-free models protons are produced when a knocked-out quark (or gluon) fragments, and such a process is not more sensitive to the nucleon size than other quark processes.

When completing this manuscript I became aware of the fact that Ref. 2 quotes Bjorken as suggesting "diquark states" as an explanation of the EMC effect in a private communication with the authors. I have no further knowledge of Bjorken's idea.

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