Disentangling Explanations of Deep-Inelastic Lepton-Nucleus Scattering by Lepton-Pair Production

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Deep-inelastic lepton-nucleus scattering has shown that the momentum distribution of quarks in a nucleon is modified by the nuclear environment. Several different explanations have been proposed. These can be distinguished by proton-nucleus scattering experiments which measure the production of lepton pairs in certain kinematic regions.

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A surprising recent discovery is that the nucleon structure function, as measured in deep-inelastic lepton-nucleus scattering[1,2] (DIS), varies with the target nucleus. This phenomenon has become known as the EMC (European Muon Collaboration) effect. Determining its precise cause would have important implications for nuclear quark distributions and wave functions. Three different classes of explanations have been proposed: enhancement of pionic components of nuclear wave functions,[3] the presence of six-quark clusters,[4] or a rescaling of the momentum-transfer dependence of the structure function.[5] All give similar results for the ratio of structure functions per nucleon for iron (Fe) and deuterium (D) (see Fig. 1). We show that proton-nucleus scattering experiments, in which a quark and an antiquark annihilate to produce a lepton pair via a virtual photon (Drell-Yan process), can help distinguish different explanations of the EMC effect.

Measurements of the nuclear (or A) dependence of the dimuon production cross section have been carried out and no such effect has been observed.[6] However, no systematic search in the most appropriate kinematic region (low x_1, high x_2; see Fig. 3) has been made.

In the basic dilepton production process a quark (or antiquark) in the projectile, carrying momentum fraction x_1, meets an antiquark (or quark) in the target carrying a fraction x_2 of the target momentum per nucleon, and they annihilate into a virtual (timelike) photon. The virtual photon then decays into a pair of real leptons. The cross section per target nucleon, $d^2\sigma/dx_1\,dx_2$, is given by

$$\frac{d^2\sigma}{dx_1\,dx_2}=\frac{K\,4\pi\alpha^2}{9s}\frac{1}{x_1x_2}\sum_a e_a^2[q_a^P(x_1)\bar{q}_a^T(x_2)+\bar{q}_a^P(x_1)q_a^T(x_2)]. \tag{1}$$

Here α is the fine-structure constant, e_a is the quark (antiquark) charge for the flavor a, $\sqrt{s}$ is the energy in the center-of-mass frame of the projectile and one target nucleon, and $q_a^{P(T)}(x)$ and $\bar{q}_a^{P(T)}(x)$ are the projectile (target) quark and antiquark momentum distributions. Recent calculations[7] strongly suggest that the QCD cross section for dilepton production "factorizes" and so can be written in the Drell-Yan form (1), even when corrections for gluonic effects are included. These effects are represented by the enhancement factor, K, which has been found to be independent of x_1 and x_2 as well as of the target and projectile.[6]

The Drell-Yan process complements DIS. To see this, recall that experiments with lepton beams measure the target structure function

$$F_2^T(x)=x\sum_a e_a^2[q_a^T(x)+\bar{q}_a^T(x)], \tag{2}$$

where x is the fraction of the momentum per nucleon of the nucleus carried by a single quark. Equation (1) can be written in terms of $F_2^T(x)$ if one assumes that the projectile ocean is SU(3) symmetric and defines proton (projectile) valence-quark distributions $v_a^P(x)=q_a^P(x)-\bar{q}_a^P(x)$. By adding $\bar{q}_a^P(x_1)\bar{q}_a^T(x_2)$ to the second term and subtracting it from the first term of Eq. (1) one obtains

$$\frac{d^2\sigma}{dx_1\,dx_2}=\frac{K\,4\pi\alpha^2}{9s}\frac{1}{x_1x_2}\left[\sum_a e_a^2 v_a^P(x_1)\bar{q}_a^T(x_2)+\frac{1}{x_2}\bar{q}_a^P(x_1)F_2^T(x_2)\right]. \tag{3}$$

Deviations of the proton ocean from SU(3) symmetry are small, so that Eq. (3) is a useful guide to our results. [The numerical work uses Eq. (1).]

Equation (3) shows that, for very small values of x_1, the comparison between a heavy nucleus and D should be similar to the DIS results. This is because the projectile ocean contribution tends to dominate. On

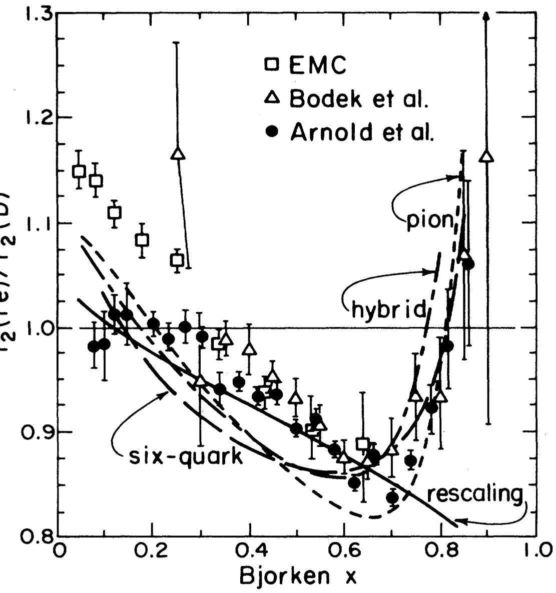

FIG. 1. Ratio of the structure function per nucleon, $F_2^A(x)/A$, for Fe to that for D. The experimental points assume $R = \sigma_L/\sigma_T$ is constant.

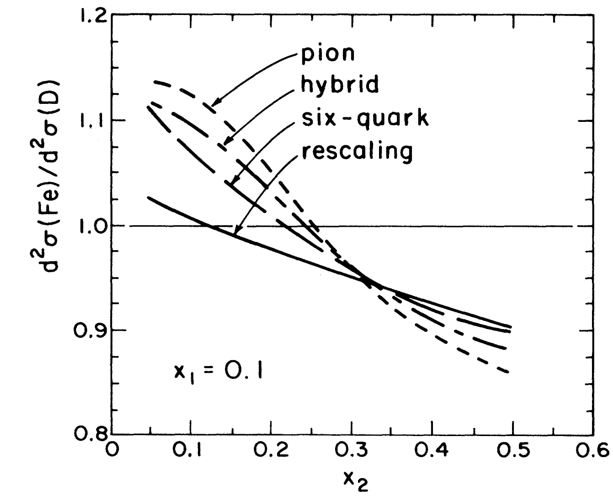

FIG. 2. Ratio of the Drell-Yan differential cross section for Fe to that for D, as a function of x_2, at $x_1 = 0.1$.

the other hand, for large x_1 the first term of Eq. (3) dominates, providing a direct probe of the ocean-quark distribution of the target.

We discuss (without criticism) each of the competing explanations and its consequences for both DIS and Drell-Yan production.

(1) *Pion enhancement (Ref. 3).*—From the point of view of ordinary nuclear structure physics, this is the most conventional proposed explanation. The pion cloud of each nucleon is augmented by the attractive interactions with surrounding nucleons, so that the chance for an incident virtual photon to interact with a pion instead of a nucleon is increased. Such contributions occur mainly for values of $x \lesssim 0.2$ in the Ericson-Thomas model but nonnegligible effects can exist for larger values in Berger, Coester, and Wiringa.[3] Thus pionic enhancement tends to increase the structure function at small x. The constraints of momentum conservation require that an increase in the momentum carried by the pions lead to a decrease in the momentum carried by the nucleons. This effect depletes (both the valence and sea parts of) the nucleon structure function over the range $0 < x < 0.7$ and here accounts for the observed reduction at midrange values of x.

$$q_a^A(x) = \int_x^A (dy/y) f_N(y) q_a^N(x/y) + \int_x^A (dy/y) f_\pi(y) q_a^\pi(x/y), \tag{4}$$

where $f_\pi(y)$ is the momentum distribution of the excess pions per nucleon in the nucleus; that of Ericson and Thomas is used. The momentum distribution of the nucleons, $f_N(y)$, is taken from the nucleon Fermi-gas distribution, as modified by the requirement that the momentum carried by pions is removed from the nucleons (see Llewellyn Smith[3]). (Effects of delta components of nuclear wave functions are ignored since they are small.[3]) The pion and nucleon quark distributions are from Badier *et al.*[8] and Parker *et al.*[9] The results for $F_2^{\mathrm{Fe}}(x)/F_2^{\mathrm{D}}(x)$ obtained with Eq. (4) and this input are shown in Fig. 1.

We also use Eq. (4) to calculate the cross section for the Drell-Yan process on a heavy nucleus. The results, displayed as a ratio of the Fe and D cross sections, are given in Figs. 2 and 3, for $x_1 = 0.1$ and 0.7. For values of $x_2 > 0.3$, use of this pionic enhancement model causes the Drell-Yan process in nuclei to be suppressed. The effect is especially significant, and detectable, at large values of x_1; it is an immediate consequence of the sea suppression in this model. The results are given for fixed $Q^2 = x_1 x_2 s$, though experiments are carried out at fixed s. (Cross-section ratios are not very dependent on Q^2.)

It is worth noting that the quark distributions of Eq. (6) are sensitive to the specific model for $f_\pi(y)$. For example, if the one of Berger, Coester,

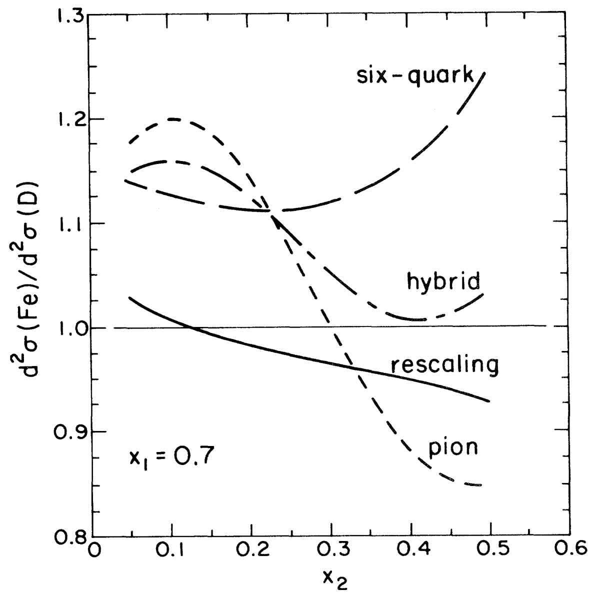

FIG. 3. Same as for Fig. 2, but for $x_1 = 0.7$.

and Wiringa (with its large extent in y) replaces that of Ericson and Thomas, the Drell-Yan ratios are enhanced for all x_2. Indeed for $x_1 = 0.7$ and $x_2 = 0.5$ the ratio obtained from Fig. 6 (solid curve) of Berger *et al.* is about 2.5.

(2) *Six-quark clusters.*—The basic notion is that nuclear wave functions include six (or more) -quark cluster components with significant probability. For specific computations we use the six-quark approach of Carlson and Havens (CH). However, the results are typical of all models in this class. According to QCD counting rules[10] the structure function of a six-quark object is very different from that of a three-quark nucleon. Thus DIS from a nucleus containing these objects differs from that on a nucleon. The resulting quark distributions[11] for a nucleus are

$$q_a^A(x) = (1-f_6)q_a^N(x) + f_6 q_a^{6q}(x), \tag{5}$$

where f_6 ($=0.3$) is the presumed fraction of the nucleons in Fe that form six-quark clusters. In this model the sea is enhanced significantly at all values of x, while the valence quarks are depleted in the region between $x = 0.1$ and $x = 0.7$. These features allow the model to describe DIS (see Fig. 1).

Although the DIS results of the Ericson-Thomas pion-enhancement model and the six-quark cluster model are very similar, the Drell-Yan cross sections are radically different (see Figs. 2 and 3). This is because the sea enhancement, prevalent for all values of x_2 in the latter model, causes a large increase in the Drell-Yan process for values of $x_1 \gtrsim 0.5$. Since the two models differ by as much as 40% in kinematic regions that are experimentally accessible, accurate Drell-Yan data can separate these two models.

(3) *Hybrid model.*—Pion exchange between nucleons is a long-range effect, while six-quark cluster formation is a short-range effect. Thus it is plausible that both are features of nuclear wave functions.[12,13] To obtain a hybrid model consistent with the DIS data it is necessary to reduce the magnitudes of the nuclear pionic and six-quark cluster components from the values used in the separate models. For the pionic model this is achieved by an increase of the nucleon bag radius from 0.7 fm (used by Ericson and Thomas) to 0.9 fm. The latter value is in better accord with nucleonic properties.[13] Furthermore, a recent (p,p') scattering experiment[14] which is sensitive to pionic enhancements has found no such effects. Thus nuclear augmentation of pions may be much smaller than originally believed. Correspondingly f_6 is reduced from 0.3 to 0.1. The resulting hybrid model contains nucleons, pions, and six-quark clusters. The quark distribution per nucleon is now

$$q_a^A(x) = \int_x^A \frac{dy}{y} f_N(y) q_a^N\left(\frac{x}{y}\right) + \int_x^A \frac{dy}{y} f_\pi(y) q_a^\pi\left(\frac{x}{y}\right) + f_6 q_a^{6q}\left(\frac{x}{1-\eta}\right), \tag{6}$$

where η is the momentum fraction per nucleon carried by pions (~ 0.03).

The hybrid model is essentially an average of the pion-enhancement and six-quark cluster models. Thus one expects that the nuclear DIS data will be reproduced and the Drell-Yan results will be roughly the average of those of models 1 and 2. That these natural speculations are borne out is demonstrated in Figs. 1–3, except at large x in Fig. 1 where the CH model lacks a correction for Fermi motion. Thus a Drell-Yan experiment that finds no A dependence will not rule out pion-enhancement or six-quark cluster formation. A reasonable, but not unique, interpretation of such a result would be that both effects are present.

(4) *Rescaling the momentum transfer (Ref. 5).*—As shown by Close, Roberts, and Ross (CRR), the Fe structure function evaluated at Q^2 is similar to that of D evaluated at ξQ^2 ($\xi \cong 2$ for the Fe tar-

get). This scale change could be due to an increase in the confinement size, but the exact mechanism is not specified. (The models of Refs. 3 and 4 incorporate some deconfinement effects.) The consequences of the CRR approach for DIS and the Drell-Yan process may be found by use of the QCD evolution equations to obtain quark distributions at ξQ^2 from that at Q^2. The features of such a procedure are well known: As Q^2 increases the valence quark distribution is suppressed at large x and (at small x) the sea is enhanced. At larger values of x, the sea is also suppressed. To obtain specific results, we use the quark distributions of Gluck, Hoffmann, and Reya[15] and compare them for $Q^2 = 25$ GeV^2 (for the nucleon target) and 50 GeV^2 (for Fe). We find that the sea is enhanced for $x < 0.1$, but suppressed for $x > 0.2$. This, along with the valence suppression, gives a reasonable explanation of the DIS data (Fig. 1). Because of the sea-quark depletion at medium x, one expects the Drell-Yan results of the CRR approach to be qualitatively similar to those of the pionic-enhancement model. This is the case, but the effects are weaker in this rescaling model (see Figs. 2 and 3).

A final question is whether an experiment would be limited by small cross sections. This is not the case; the computed cross sections for $x_1 = 0.7$ and $x_2 = 0.5$ are comparable with the ones measured to 10% accuracy in typical Drell-Yan experiments.[6]

Different models that "explain" the nuclear DIS data lead to different sea-quark distributions. This could enable the Drell-Yan process to ferret out the correct explanation.

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