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The A dependence of dilepton production

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1. INTRODUCTION

The discovery [1] in 1982, by the EMC group, that the structure function $F_2(x)$ per nucleon is different in iron than deuterium was the first evidence that the structure of the nucleon might be altered in nuclei. Much more extensive and precise data have been taken since the original discovery. This body of data is now quite consistent [2], and many of the features of the original "EMC effect" remain intact. There have been a variety of theoretical explanations of the data, but none are totally compelling. The deep-inelastic-scattering (DIS) data for the ratio of $F_2^{\text{Fe}}(x)$ in iron to $F_2^{\text{D}}(x)$ in deuterium are shown in Figure 1 for the region $0.03 \leq x \leq \sim 1.0$. Over this region in

Figure 1. The ratio of the structure function $F_2(x)$ per nucleon measured in iron (Fe) and deuterium (D). The data are a compilation of several measurements.

x , both suppression and enhancement is observed. Given the fact that there is no way of reliably calculating the structure function for a free nucleon, it is not surprising that there is no satisfactory explanation of the small (10–20%) alterations that take place in nuclei. All the suppressions and enhancements, however, appear to be quite regular and increase as a function of A . To discuss these effects, it is useful to distinguish four regions. All effects increase as a function of A with the ratio $F_2^A(x)/F_2^D(x)$ approaching 1 for all x as $A \rightarrow \infty$. The effects to be noted are: (1) apparent shadowing in the region $x < 0.1$; (2) enhancement in the region $0.1 \leq x \leq 0.3$; (3) decrease of the ratio between $0.3 \leq x \leq \sim 0.65$; (4) followed by an increase in the region $\sim 0.65 \leq x \leq 1$. This latter rise is ascribed to Fermi motion of the nucleons within a nucleus and appears to be accounted for by relatively straightforward calculation.

2. THE DRELL-YAN PROCESS

In order to provide additional information on the EMC effect, our collaboration [3] (FNAL E772) undertook a measurement of the ratio of the sea quark structure function in nuclei relative to that in deuterium, i.e., $R(A/D) = \bar{q}^A(x)/\bar{q}^D(x)$. This study was carried out using the Drell-Yan [4] process. If all of the “EMC effects” at $0.03 \leq x \leq 0.4$ are ascribable to the sea quarks, the alteration in the ratio $R(A/D)$ would be very dramatic, as shown in Figure 2. There exist explicit models of the EMC

Figure 2. The prediction for the ratio $R = (\bar{q}(x)|_{Fe})/(\bar{q}(x)|_D)$ if the deviations from unity shown in Figure 1 are entirely ascribed to sea quarks.

effect that would predict $R(A/D)$ to be large, for example, the pion excess model [5] in which momentum is transferred from valence quarks to the sea via a pionic excess generated in finite nuclei. The idea of using the Drell-Yan process to access the sea quark distribution came from a variety of authors [6], all seeking additional information to interpret the EMC effect.

The lowest-order diagram for the Drell-Yan process is shown in Figure 3. In this case, a quark (antiquark) from the beam projectile annihilates in an antiquark (quark) from the target, forming a virtual photon of mass M , which in turn decays into a dilepton pair ($\ell^+\ell^-$). The cross section for this process can be written

$$\frac{d\sigma}{dM dx_F} = \frac{K 8\pi\alpha^2}{gM^3} \sum \frac{e_i^2(x_b x_t)}{x_b + x_t} [q_i(x_b)\bar{q}_i(x_t) + \bar{q}_i(x_b)q_i(x_t)] , \quad (1)$$

where e_i is the charge of a quark with flavor i , and $q_i(x_b)$ is the probability that a beam quark of flavor i carries a momentum fraction (x_b), similarly for the target quarks (x_t). The factor K is present to account for all higher-order QCD interactions not adsorbed into the definition of the quark structure functions as determined in deep inelastic scattering.

Figure 3. Diagram of the Drell-Yan process.

As we are interested in the behavior of the structure functions relative to those in deuterium, it will be assumed that the factor K cancels in ratios of the Drell-Yan yield formed over the same range of x_b and x_t .

The quark structure functions for the proton are now rather well known. They do not directly enter the result, as the structure functions of the incident proton enter as a common factor in the ratio. However, we do need to know that the values of x_b and x_t used to extract $\bar{q}(x_t)$ satisfy the condition

$$q(x_b)\bar{q}(x_t) \gg \bar{q}(x_b)q(x_t) . \quad (2)$$

With the above, the relative sea quark distribution in the target nucleus is extracted. For an incident proton, the ratio when $x_b \gg x_t$, i.e., $x_F > 0.2$, of the Drell-Yan yield is therefore

$$\frac{\left. \frac{d\sigma}{dM dx_F} \right|_A}{\left. \frac{d\sigma}{dM dx_F} \right|_D} \frac{2}{A} = \frac{4u(x_p)\bar{u}^A(x_t) + d(x_p)\bar{d}^A(x_t)}{4u(x_p)\bar{u}^D(x_t) + d(x_p)\bar{d}^D(x_t)} , \quad (3)$$

which, in the limit that $x_p \rightarrow 1$, gives the simple result that

$$\frac{\left. \frac{d\sigma}{dM dx_F} \right|_A}{\left. \frac{d\sigma}{dM dx_F} \right|_D} \frac{2}{A} \xrightarrow{x_p \rightarrow 1} \frac{\bar{u}^A(x_t)}{\bar{u}^D(x_t)} \simeq \frac{s^A(x_t)}{s^D(x_t)} , \quad (4)$$

assuming that the sea and $\bar{u}$ distributions are the same.

The kinematics of the Drell-Yan process is straightforward and leads to the following results in the center of mass,

$$M^2 = S x_b x_t , \quad (5)$$

where S is the squared center-of-mass energy

$$S \cong 2M_N E_B , \quad (6)$$

M_N is the nucleon mass, and E_B is the beam energy. In the lab system we have

$$M^2 = (p_{t+} + p_{t-})^2 \cong p_{t+} p_{t-} \theta^2 , \quad (7)$$

where θ is the laboratory angle between the dileptons and $p_{t\pm}$ is their momentum. The total energy in the lab system of the lepton pair is

$$E_{t+} + E_{t-} = E_p x_b , \quad (8)$$

where E_p is the laboratory energy of the incident proton and

$$E_{t+} - E_{t-} = E_p x_b \cos \theta_{c.m.} , \quad (9)$$

where $\cos \theta_{c.m.}$ is the center-of-mass angle ($0 \leq \theta_{c.m.} \leq \pi$) between the lepton pair.

3. THE EXPERIMENT

The experiment was carried out using the 800-MeV external proton beam at FNAL. It uses the double-bend dilepton spectrometer previously used in E605 [7]. The targets employed are $^2\text{H}_2$, ^{12}C , ^{40}Ca , Fe, and W. Each is carefully prepared to minimize any systematic error in relative yield and they are frequently interchanged in the course of a run.

The incident beam current is limited to 2×10^{12} per 20-s spill to keep multiple hits in the wire chambers below a rate that would introduce ambiguity into the tracking. The angular acceptance of the spectrometer system allows an approximately 5% acceptance for Drell-Yan events. Figure 4 shows the x_b and x_t distributions, while

Figure 4. Scatter plot of the dileptons recorded for different magnetic spectrometer settings as a function of x_b and x_t .

Figure 5 shows the acceptance-corrected mass spectrum obtained for the three settings of the spectrometer. The overall resolution is the order of 100 MeV and the dimuon pairs from the decay of J/ψ , ψ' , and $\Upsilon(1s)$, $\Upsilon(2s)$, $\Upsilon(3s)$ are all well resolved from the underlying Drell-Yan continuum.

Figure 5. The acceptance-corrected mass spectrum $[M = (Sx_b x_t)^{1/2}]$ from each of the spectrometer settings.

4. RESULTS

The first observation to be made is that the measured A dependence of the integrated observed Drell-Yan yield over the range $0.05 \leq x_t \leq 0.3$, $4.2 < M_{\mu^+\mu^-} < 12$ GeV is very weak. Parameterizing the relative yield as

$$\frac{Y_{DY}(A)}{Y_{DY}(Z)} = \text{const } A^{\alpha_{DY}},$$

we find $\alpha_{DY} = 0.998 \pm 0.001$. This result (shown in Figure 6) is much more precise than the previous experiments and supports the ideas of several theorists [8], that the yield of hard processes such as DY is A independent. Thus, even though the soft partons in the proton are greatly altered, the longitudinal momentum of the hard (valence) quarks ($x_b > 0.2$) is only slightly altered. This gives greatly increased confidence that

Figure 6. The A dependence of the yield per nucleon for various processes (DY, J/ψ production, γ production) that produce $\mu^+\mu^-$ pairs. The yield of each process p is parameterized as $Y_p(A) = C_p A^{\alpha_p}$.

the underlying structure functions of the target are being measured. Figure 7 shows the results for the ratio of the yield of Fe/ ^2H , along with earlier results [9] achieved with neutrino deep inelastic scattering. There is obviously an enormous improvement in the quality of the data, which shows very little, if any, enhancement in the relative number of sea quarks per nucleon in Fe relative to those present in ^2H . One can see that there is evidence for a "shadowing" effect for $x < 0.1$. The small depletion at $x < 0.1$ is consistently seen in all our data, and it increases with A , just as in DIS and, further, there is good agreement as to its magnitude between our measurements and those in DIS. This is surprising, as a virtual photon in Drell-Yan is time-like and that of DIS is space-like. If shadowing, i.e., the attenuation of the virtual photon, is not the explanation, then the observed depletion must come from a relative reduction of the structure function at low x . Figure 8 shows all the E772 data for the ratio of the Drell-Yan yields from C (a), Ca (b), Fe (c), and W (d) relative to ^2H . Figure 7(c) shows the Fe/ ^2H ratio compared to three theories inspired by the EMC effect. The pion excess model [5] predicted an increase in the number of pions per nucleon in heavier nuclei due

Figure 7. The ratio $R(\text{Fe}/\text{D}) \equiv (\bar{q}(x_t)|_{\text{Fe}})/(\bar{q}(x_t)|_{\text{D}})$, as determined in this experiment (squares) and previous [9] neutrino DIS (diamonds).

Figure 8. Ratio $(\bar{q}(x_t)|_A)/(\bar{q}(x_t)|_D)$ for $A = \text{C}, \text{Ca}, \text{Fe},$ and W , as a function of x_t . Insert c for the Fe/D ratio shows the predictions of three models, discussed in the text. Insert d for the W/D ratio also shows the $F_2(x)$ ratios measured in DIS.

to meson exchange. Various versions of the quark cluster models [10] also predicted a relative enhancement of the sea in heavier nuclei. The data appear consistent with the Q^2 rescaling arguments [11], though these models do not of course account for the “shadowing” effect at $x \leq 0.1$. Thus, the data gathered in this experiment support the following conclusions:

- 1 There is no evidence for the enhancement of sea quarks in the region $x \leq 0.3$.
- 2 The depletion seen in this DY ratio below $x = 0.1$ is totally consistent with the observation seen in DIS. As the ratio of sea to valence is well below 0.5 in the region $0.05 \leq x \leq 0.1$, the valence quarks are “shadowed/depleted” to the same degree as the sea quarks. This is an interesting new fact that awaits explanation.

5. DILEPTON PAIRS FROM VECTOR MESONS

Even though the gluonic sector carries roughly one-half of the proton’s momentum at $Q^2 \sim 20 \text{ GeV}^2$, there are very few direct measurements on this sector. No electroweak process directly couples to gluons, so that glue is generally viewed indirectly. There is some empirical evidence [12] that gluon fusion is principally responsible for the formation of heavy quark pairs ($c\bar{c}$, $b\bar{b}$, etc.). In this experiment (E772), several $J^\pi = 1^-$ states of the $c\bar{c}$ and $b\bar{b}$ states are observed via their $\mu^+\mu^-$ decay. I do not want to go into great detail on this subject, but want to share with you our results for this process as it bears both on the much-discussed issue of color transparency and production of these resonances in relativistic heavy-ion collisions.

Figures 4 and 5 clearly show the yields for $J/\psi(1s)$, $\psi'(2s)$, and the $\Upsilon(1s)$, $\Upsilon'(2s)$, and $\Upsilon(3s)$. Figure 9 shows the ratio of the J/ψ yield for C, Fe, and W relative to H_2 as a function of $x_F = x_t - x_b$. Clear evidence for an A and x_F dependence is seen in this figure. The A dependence is summarized in Figure 6, which shows the value of α obtained integrating over x_F and assuming the yield is given by

$$Y(A) = cA^\alpha.$$

Interestingly, the yield for ψ' shows the same A dependence as J/ψ . Calculations using wave functions that reproduce the $c\bar{c}$ energy spectrum show the ψ' to be twice as extended as the ψ . While it might be tempting to treat the A dependence as arising from an A dependence of the gluon structure function, Figure 10 shows this to be unlikely. It shows the ratio for J/ψ production from Fe/D by incident protons at $E_p = 200 \text{ GeV}$ [12] and our data at $E_p = 800 \text{ GeV}$. Figure 10(a) shows the two ratios as a function of $x_F \equiv x_b - x_t$, wherein both experiments appear similar. However, when this ratio is converted to a function of x_t , it is clear that the two measurements do not yield a common target structure function. The relative gluonic structure functions extracted from NA10 [13] and this experiment are very different. Progress is required if the yield

Figure 9. The ratio of J/ψ production per nucleon for C (squares), Fe (diamonds), and W (squares), relative to D. The ratio is shown as a function of $x_F \equiv x_b - x_t$.

Figure 10. (a) The ratio of J/ψ production per nucleon for Fe/D as a function of x_F for $E_p = 200$ GeV (open squares) and 800 GeV (solid squares). Note that the ratio is specified by the quantity α where $\alpha - 1 = [\ln(Y_{Fe}/Y_D)]/3.25$. (b) Same ratio as 10(a), but now as a function of x_t .

of heavy-quark pairs is to be used as a measure of the target and beam gluonic structure functions.

The higher mass of the Υ resonances makes the application of QCD easier and more reliable; therefore, one might believe that gluonic structure functions could be more reasonably extracted from the upsilon yield. The x_F distribution for the ratio of

the Υ yield of W/D is shown in Figure 11(a), while the corresponding distribution is shown in Figure 11(b) as a function of x_t .

Figure 11. (a) The ratio of $\Upsilon(1s)$ production per nucleon for W/D. The ratio as a function of x_F is given by the quantity α' where $\alpha' - 1 = [\ln(Y_W/Y_D)]/4.52$. (b) Same ratio as 11(a), but as a function of x_t . (c) Same ratio as 10(a), but as a function of the transverse momentum carried by the $\mu^+\mu^-$ pair.

It appears that there must be considerable nuclear medium effects associated with the J/ψ and Υ yields. If that is not the case, the very large A dependence would require very depleted gluon structure functions in nuclei. This large depletion of glue would in turn present a severe problem for the momentum sum rule. Fortunately, the data do not support their use for the extraction of gluon structure functions as there is no consistent result from various data sets.

6. COMMENTS AND CLOSING REMARKS

Before closing, allow me to make a few general observations on where this area of research may be heading and the role of a high-energy ($E \geq 20$ -GeV) CW electron accelerator. It will be necessary to use the Drell-Yan process to extend the A dependence of $\bar{q}(x)$ out to $x \sim 0.6$ with good statistics. If sea quarks are in nucleons, then they should show the effects due to Fermi motion. Because the sea quark distribution falls rapidly, it shows enhancement due to Fermi motion at appreciably smaller values of x_t ($x_t \sim 0.4$) [14]. To pursue the A dependence of $\bar{q}(x)$ to much smaller values of

x_t will require using Drell-Yan pairs with masses below the J/ψ (3.1 GeV). Currently, only pairs with mass greater than 4 GeV have been used. With the constraint,

$$\frac{M_{\min}^2}{2M_p E_t} < x_b x_t \quad ,$$

it is readily seen that to achieve $x_t \sim 10^{-3}$, either a collider must be used or the results extracted from using low-mass dilepton pairs. There may be an acceptable window near $M = 2$ GeV but the possibility that higher twist corrections at such a Q^2 might obscure the results needs to be investigated.

To further effectively pursue the EMC effect probably requires determination of the A dependence of *flavor-specific* structure functions. In particular, it would be most significant to obtain the A-dependence of the gluon structure function; however, there does not exist any clear experimental program that would achieve this. Neutrino DIS and Drell-Yan experiments have the possibility of obtaining flavor-specific quark structure functions. If electro-DIS is to further contribute to elaborating on the EMC effect, it will be via coincidence experiments that effectively tag the struck quark. Given our present understanding, this will be at best a statistical tagging and hence there will be considerable difficulty extracting distributions that are smaller than, say, 10% of the dominant yield.

The polarization that can be readily achieved with a CW electron beam can potentially be an important factor, but it will require polarized targets of sufficient mass and resilience to carry out meaningful experiments. It also appears that even with the most ideal polarized target, the experiments will be limited to very light nuclei ($A < 14$) because, at most, two (in odd-odd nuclei) nucleons can be aligned via nuclear polarization. Thus, it is not clear where a high-energy CW electron facility will impact the A dependence observed in DIS.

There are, of course, a host of other issues to be studied. Higher twist is a difficult pursuit and would be an extremely important element in the program of proceeding from QCD to hadronic and nuclear physics. As much of higher twist has to do with quark-quark correlations, it conceptually has much in common with the ever evasive "short-range correlations" of nuclear physics. In QCD, the theoretical concepts seem quite clear but complex. With no real examples of higher twist from DIS experiments to work with, little progress has been made, but the future could be brighter.

The study of hadronization, along with color transparency, would doubtless benefit greatly from such an electron facility. The issue here is an evaluation of the importance of this topic in the overall scheme of nonperturbative strong interaction physics and the outline of a set of experiments that would resolve the principal issues.

A CW 20-GeV facility operating over the last decade would have contributed enormously to all of the important topics at the vital interface between quark-gluon and baryon-meson physics. Its role for the future could be as crucial. The role of such

a facility must be investigated most energetically and expeditiously, so as not to be postponed beyond a time where its impact could be decisive.

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