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THE NUCLEAR DEPENDENCE OF PARTON DISTRIBUTIONS

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ABSTRACT

I review the emerging information on the way quark, antiquark, and gluon distributions are modified in nuclei relative to free nucleons. I place particular emphasis on Drell-Yan and ψ production on nuclei and caution against premature use of these as signals for quagm in heavy-ion collisions.

INTRODUCTION

If we are to identify the formation of quark-gluon plasma in heavy-ion collisions by changes in the production rates for ψ relative to Drell-Yan lepton pairs, then it is important that we first understand the "intrinsic" changes in parton distributions in nuclei relative to free nucleons. So, I will review our emerging knowledge on how quark, antiquark, and gluon distributions are modified in nuclei relative to free nucleons, and briefly summarize the emerging theoretical consensus.

PARTONS IN NUCLEI

The best known nuclear distortion is that of the EMC effect which reveals a modification of the valence quark distributions in nuclei relative to those in free nucleons.

All experiments now show broad agreement.^{1,2} The rise in F_A/F_N at $x > 0.7$ is due to Fermi motion causing the structure function F_A to leak out to $x > 1$; dramatic as this appears, it occurs where $F_{A,N} \approx 0$, and is, in fact, a very minor contributor to the overall phenomenon. Indeed, overall, the effect is a subtle 10% affair, and

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we don't need to rewrite the nuclear physics textbooks. As $x \rightarrow 0$, we are beginning to see evidence for shadowing, a subject on which theory is now also starting to develop.³

QUARKS IN NUCLEI

In the "intermediate" region $0.2 \leq x \leq 0.6$ the ratio falls below unity as (valence) quarks lose momentum due to nuclear binding. The A dependence was successfully predicted in advance of data⁴ and is rather well understood. It was first predicted in the context of the rescaling analysis and subsequently verified by experiments at SLAC.¹ Qualitatively, the effect is driven by the chance that there is a nearby nucleon correlated with the target nucleon. Reference 4 made a geometrical model and predicted δF_2^A for all A . (As the volume of a nucleon is only about 40% of the available volume, the two-nucleon contribution is $\leq 10\%$ effect, and three-body and higher contributions can be ignored.) The fit is excellent and shows that the EMC effect is sensitive to details of nuclear structure, reflected in $\rho^A(r)$ as a result of which significant fluctuations are predicted at small A which have yet to be studied. At large A the behavior is smooth and it is safe to interpolate. Thus, one can infer the $F_A(x)$ when $A =$ tungsten, say, and use this as input to $\pi W + \mu\bar{\mu} \dots$ analyses for example.

A common feature of models is that the degradation of the valence quarks transfers energy momentum to some other component (gluons and $q\bar{q}$ in rescaled QCD⁵ or the partons in the π that are responsible for nuclear binding).^{6,7} Thus, they generate an increased sea in nuclei relative to that measured in free nucleons. In turn, this implies that $F_A/F_N > 1$ as $x \rightarrow 0$. However, this predicted enhancement will probably be blacked out by shadowing (which has not been incorporated in these models so far). Mueller and Qiu⁴ have begun to illuminate us about the x and Q^2 dependence of nuclear shadowing; the first attempts at making a quantitative combination of their work with "soft π "^{6,7} or rescaled QCD⁵ are now appearing.^{8,9} I will discuss these ideas later; first I will concentrate on the empirical situation concerning parton distributions in nuclei with specific reference to the Drell-Yan process.

If $x_{1,2}$ refers to the beam and target partons, $x_F = x_1 - x_2$, and $x_1 x_2 = Q^2/s$, then the ratio of cross sections for some fixed Q^2/s is

$$\frac{\sigma^{bA}}{\sigma^{bN}} \sim \frac{\bar{q}^b(x_1)q^A(x_2) + q^b(x_1^-)q^A(x_2)}{\bar{q}^b(x_1)q^N(x_2) + q^b(x_1^-)q^N(x_2)}$$

where sum over flavors weighted by their squared charge is understood. In the case of π^- beams, if $x_2 > 0.2$ so that $\bar{q}^A \ll q^A$, the DY process is dominantly due to \bar{q}^π annihilating with $q^{A,N}$. Thus, in this kinematic regime

$$\frac{\sigma^{\pi-A}}{\sigma^{\pi-N}} \sim \frac{u^A(x_2)}{u^N(x_2)} \sim \frac{F^A(x_2)}{F^N(x_2)}$$

This is the same ratio as measured in inelastic lepton scattering ("EMC effect") and must be obtained here too if factorization is valid. Thus, we should not be surprised by the results from NA10¹⁰ who study

$$\frac{\sigma(\pi^- W+\mu^+ \mu^- \dots)}{\sigma(\pi^- D+\mu^+ \mu^- \dots)}$$

and by varying Q^2 and x_F can separate both the pion and target structure functions. In Ref. 10 they exhibit the resulting ratio of $q^A/q^N(x_2)$ and $\bar{q}^{\pi(A)}/\bar{q}^{\pi(N)}(x_1)$.

The latter should be unity and is within errors when one combines data from two energies, 140 GeV and 286 GeV incident π beams. (However, if one restricts attention to the lower energy sample, the situation is more messy and the pion distributions do not seem to factorize. Why this should be is unclear to me, but bear it in mind as an empirical observation for later reference.)

So the message is: do not be misled by $\sigma = A^\alpha$, $\alpha \approx 1$ for Drell-Yan pair production on nuclei. While this may be approximately true for the total rate, there can be (and are) non-trivial effects in x and p_t^2 . A depletion at large x may be compensated by an enhancement as $x \rightarrow 0$ for example. The kinematic conditions of experiments may emphasize different regions of x for the beam and target. The extent

which A-dependent effects will arise depends on $\bar{q}^A(x)$ and $g^A(x)$, about which we know almost nothing. Rescaling and pion models imply that both $\bar{q}(x, Q^2)$ and $g(x, Q^2)$ have non-trivial A dependence; moreover, shadowing effects will modify them as $x \rightarrow 0$. Empirical information is only now beginning to emerge.

ANTIQUARKS IN NUCLEI

The Drell-Yan process with incident nucleons can probe q in the target if suitable kinematics are chosen, e.g., $x_1 = 0.7$ and $x_2 \ll x_1$. An investigation of this in various models has been made by Bickerstaffe et al.¹¹ and by Berger et al.⁷ As an example, in Fig. 1, I show the predictions for $\bar{q}^A/\bar{q}^N(x)$ in iron in three models compared with information gleaned from CDHS.¹³ The dramatic rise in the Berger-Coester model at $x > 0.3$ is due to their prediction that \bar{q} leak out to moderate x values in nuclei. However, it is illusory to some degree as both \bar{q}^A and \bar{q}^N are vanishingly small; even so, experiment E772 may be able¹² to test this. Independent of specific models, it is an interesting question whether \bar{q} leak to "large" x in nuclei as this will have a bearing on the Q^2 shape of Drell-Yan pairs in nuclei which may differ from the ψ production (produced by gluons) and potentially provide a background to the plasma signal sought in heavy-ion collisions.

Recently WA25 and WA59 in collaboration have studied the EMC effect using ν and $\bar{\nu}$ interactions in neon and deuterium. The x, y distributions allow separation of quark and antiquark distributions, and there is some indication that the sea decreases in going from deuterium to neon; however, these data are probably being dominated by nuclear shadowing, like the electromagnetic data for $x \leq 0.1$, again highlighting the need to see how shadowing modifies the curves in Fig. 1 at small x .

GLUONS IN NUCLEI

Insofar as inelastic $\gamma A \rightarrow \psi + \dots$ proceeds via photon-gluon fusion and $NA \rightarrow \psi + \dots$ involves gluon-gluon fusion, these processes probe $g^A(x)$. There have been early claims that $g^A > g^N$ ($x \sim 0.05$), this based on the EMC data¹⁴ for $(\gamma Fe \rightarrow \psi)/(\gamma D \rightarrow \psi \dots)$. Expressed as

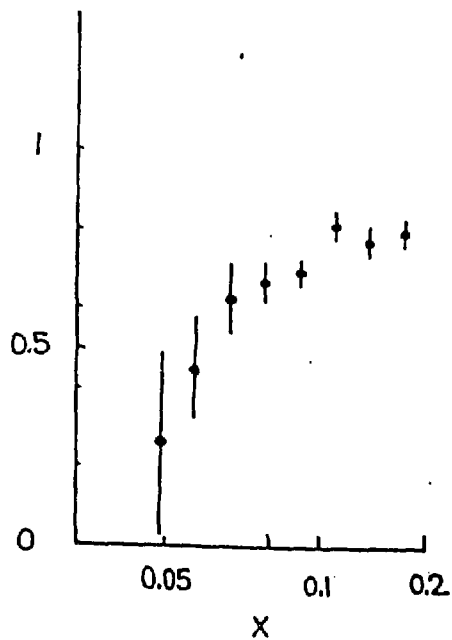


Fig. 2. Ratio of ψ production in π^+W/π^-W^-Be from E537 (Ref. 14) which is indicative of $g^W/g^{Be}(x)$, plotted against x -Bjorken for the nuclear target (x_2).

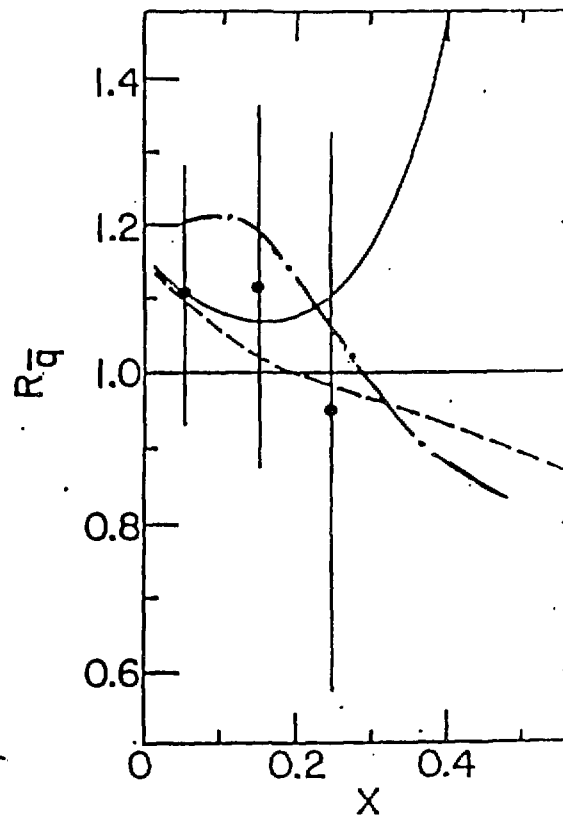


Fig. 1. Data from Ref. 11 on the ratio $\bar{q}_{Fe}^+/q_{D}^-(x)$ from neutrino scattering. Here $q = (u+d=2s)$. The solid curve illustrates predictions of pion exchange model (Refs. 8 and 11), the dot-dash is the pion model of Ref. 7, and the dashed curve is the rescaling model, Ref. 6.

At this gave $\alpha = (1.10 \pm 0.03 \pm 0.04)$. However, it is now less clear whether coherent ψ production (for which $\alpha \approx 4/3$) has been entirely removed from the data. Indeed E691 (Sokoloff et al.) report¹⁵ that (at $Q^2 = 0$)

$$\begin{aligned}\alpha_{\text{coherent}} &= 1.40 \pm 0.06 \pm 0.04 \\ \alpha_{\text{incoherent}} &= 0.94 \pm 0.02 \pm 0.03\end{aligned}$$

This suggests that gluons are shadowed in nuclei.

There are also confusing signals¹⁶ coming from E537 who probe the gluon distribution with $\pi^- W/\text{Be} + J/\psi \dots$ at 125 GeV, measuring the x_F distributions and thereby enabling $g^{W/\text{Be}}$ to be measured for $x_{Bj} > 0.2$. If $x_F = x_1 - x_2$, then for J/ψ production at 125 GeV

$$x_F \approx \frac{1}{25x_2} - x_2$$

Thus, we can replot the data from E537 against x_2 (Fig. 2). This is equivalent to $g^W(x)/g^{\text{Be}}(x)$ only if $g^{\pi(W)} \neq g^{\pi(\text{Be})}$ cancels out. However, we have no immediate way of knowing if this is true empirically as $Q^2 (=m_\psi^2)$ is fixed. Prima facie, one may justifiably be worried. First, which is theoretical prejudice, if Fig. (2) is interpreted as $g^{W/\text{Be}}(x)$, it implies that gluons are significantly shadowed for x as large as 0.2. Our understanding of shadowing is still rather primitive, but such behavior would be against all current models. However, the Na(10) data at 140 GeV were confusing, as I mentioned earlier, and things only became clear when the 286-GeV data were considered. Therefore, in the E537 case I will remain cautious until higher energy ψ production data are available.

Experiment E672 at Fermilab is measuring¹⁷ $\pi^- A + \psi$ on four nuclei at 530 GeV. I await their "high energy" extraction of $g^{A/N}(x)$. Until the conundrum of energy dependence (i.e. the non-factorization of the partons in the incident beam) is settled, I conclude that $g^{A/N}(x)$ probably falls as $x \rightarrow 0$, in qualitative agreement with the shadowing phenomenon, but the quantitative measure is unclear.

Thus, with the exception of valence quarks for $x > 0.2$, there is little or no evidence for non-trivial behavior for $q^{-A/N}$ and $g^{A/N}$. It

is imperative to know these quantities much better, and to understand the anomalous energy dependence manifested by NA(10), and implicitly hinted at by E537. Until we do, then we cannot, with any confidence, use J/ψ relative to Drell-Yan production in AA collisions as a signal for quark-gluon plasma formation. Note that if the E537 experiment's dramatic suppression of nuclear glue is true, then ψ production per nucleon in heavy-ion collisions will be markedly suppressed relative to that in pp or even pA interactions. There is no reason to anticipate such drama for Drell-Yan.

SHADOWING

With the recent work of Mueller and Qiu³ we have a model for shadowing that is rooted in QCD. As $x \rightarrow 0$, the evolution equations imply that the number densities of gluons become very large. Gluons (and quarks) from different nucleons should interact with each other and reduce the number densities through annihilation. These annihilations are then responsible for nuclear shadowing.

For our present purposes, we need only be concerned with the x dependence of the input shadowed distributions. Arguments based on the longitudinal length scales probed suggest that shadowing vanishes if $x > x_n \approx 1/2 r_m$ (m = nucleon mass, r its radius) and becomes total if $x < x_A \approx 1/2 R_m$ (R = nuclear radius). Qiu then interpolates; his formula for the shadowing ratio $F^A/F^N(x)$ may be written (Fig. 3)

$$F^A/F^N(x) = R(x) = \begin{cases} 1 - K \left(\frac{x_n}{x} - 1 \right) & (x_A < x < x_n) \\ 1 - K (A^{1/3} - 1) & (0 < x < x_A) \end{cases}$$

where K is a constant to be fitted by $x \rightarrow 0$ data. We thus see that R is a universal curve whose only A dependence is the saturation point.

We can now see the effect of shadowing combined with EMC-inspired models. For heavy nucleus B , the enhancement is generally expected to be greater than for a light nucleus A . On shadowing these expectations with Qiu's universal curve, one finds that the crossover from enhancement to shadow at small x will be $x(B) < x(A)$ (Fig. 4). This will be a subtle effect and more analysis is needed to see precisely what the values of the crossover should be. The empirical extraction

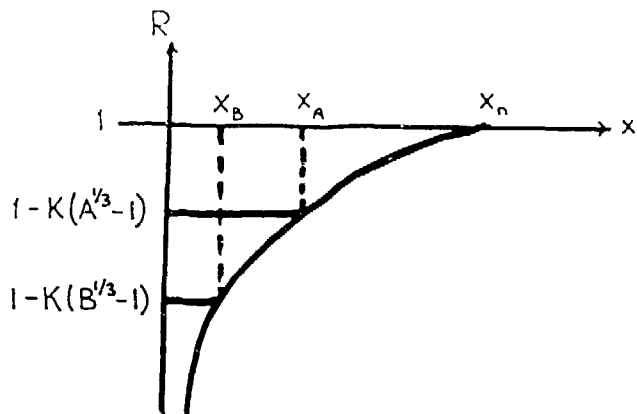


Fig. 3. A dependence of shadowing in Mueller-Qiu model.

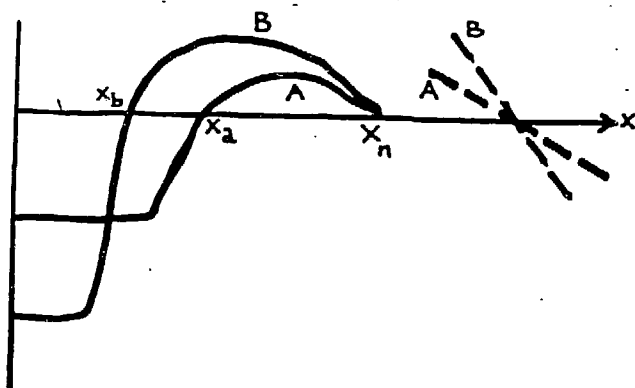


Fig. 4. Effect of Mueller-Qiu shadowing combined with enhancements in naive EMC models. Note the crossover $x_b < x_a$.

o. the crossover $x_c(A)$ will be an interesting exercise in the future.

The emerging data suggest that $x(B) > x(A)$, contrary to the above. This may imply that x_n is A-dependent. Qiu assumed, for simplicity in a first orientation, that $x_n \sim 1/R$ where R is the nucleon size — this being a measure of the distance scale for quarks from neighboring nucleons to "interfere". However, the A-dependence of the large x data ("EMC effect") suggests that quarks in neighboring nucleons have a greater chance to interfere as A increases; therefore the interference distance scale decreases and x_n increases with A. This qualitatively mimics the trend of the shadowing data but, of itself, does not seem to be sufficient. Berger and Qiu⁹ in a recent ANL preprint have proposed a similar idea but have refrained from making a quantitative comparison. I will now look at the A dependence of small x data in more detail.

We take the original rescaled QCD, or the similar curves of the pion models of the EMC effect, and shadow them using Qiu's shadowing ansatz. Note that, for a given A, a single scale controls shadowing since he assumes that saturation ($x = x_A$) and onset ($x = x_n$) are related as follows

$$\frac{x_A}{x_n} = \frac{R_n}{R_A} = A^{-1/3}.$$

When we compare the resulting curve with the data for carbon (smallest A, largest x_A), we find that the crossover point (x_a) is predicted at larger x than in the data. One must find some way of translating the curve to smaller x values.

If we are to preserve the $Q^2 = 0$ ($x < x_A$) saturation value, one way to achieve an effective shift is to reduce x_A . However, this is probably unphysical: $x_A \sim R_A^{-1}$ and so one achieves saturation at dimensions greater than those of the entire nucleus. Our present taste is that shadowing is complete at distances no greater, and maybe even less, than nuclear dimensions. Therefore to attain the desired translation, we choose to shadow only the sea (a rationale being that, in Müller and Qiu's model, this component, and not valence quarks, is responsible for shadowing).

One gets an acceptable fit to carbon data in this way: shadow the sea in the rescaled QCD or pion models of EMC.

Now proceed to the A dependence. As pointed out earlier, the naive prediction that x_a (Fig. 4) decreases as A increases is inconsistent with data. This bad result is probably generally true in any single scale model. Berger and Qiu have recently suggested that two length scales are involved (surface to volume effects provide the new degree of freedom in their work) and can thereby reverse the dependence, at least qualitatively.

Inspired by their idea, we have begun to develop a unified picture of the A dependence for all x. This model has similar empirical features, but differences in detail, to that of Ref. 8. It is rooted in our previous successful prediction⁴ of the A dependence at large x. With increasing A, there is an increasing chance for a parton in one nucleon to be "aware" of constituents of neighboring nucleons; the mean distance between the members of such "overlapping" nucleons decreases and hence x_n increases with A.

This is similar to Ref. 8. While it may agree with the trend of the data for $x > 0.1$, it does not, alone, describe the most dramatic A dependence in the new EMC data, namely $x_a(A)$. Reference 8 and the present ideas have very little to say about the actual data; the data at $x < 0.1$ seem to require a radical re-evaluation of $x_a(A)$.

So we return to carbon, with which there exists a reasonable fit, and look for guidance: we were able to fit carbon with its canonical $x_A \sim R_A^{-1} \sim x_n A^{-1/3}$. One easily verifies that the most dramatic effects arise from changing $x_A(A)$. Qiu's assumption is that $x_A \sim A^{-1/3}$; we illustrate the other physical extreme - namely that $x_A =$ constant ($\equiv x_{\text{carbon}}$, motivated by our successful "fit" to that data). Physically this corresponds to, at large Q^2 , saturation of shadowing occurring once a few nucleon dimensions only are exceeded. Such a behavior is consistent with data, but it is far too soon to claim that data imply this. At this stage, we note only that it is $x_A(A)$ which seems to control most radically the data, and that if $x_A/x_n \sim A^{-n}$, then n is probably nearer to zero than 1/3. A dynamical model for this is awaited.

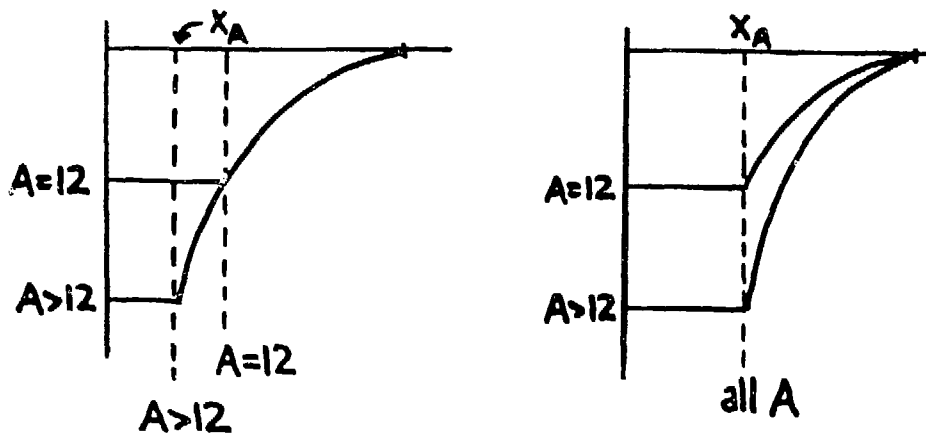


Fig. 5. Effect of preserving the depth ($\pi + 0$) but modifying x_A .

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