**High Energy Nuclear Quasielastic Reactions:
Decisive Tests of Nuclear Binding/Pion Models of the EMC Effect**

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**PREPARED FOR THE U.S. DEPARTMENT OF ENERGY
UNDER GRANT DE-FG06-90ER40561**

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**High Energy Nuclear Quasielastic Reactions:
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Abstract

The light-cone nucleon momentum distributions obtained from non-relativistic spectral functions or given by nuclear binding/pion models are often used to analyze high Q^2 quasi-elastic and deep-inelastic (e, e') reactions. We demonstrate that in such models the presence of non-nucleonic components causes the scattering from forward and backward moving target protons to be significantly different. Other models do not have this property. The sensitivity of current $(e, e'p)$ and (p, pp) color transparency experiments is sufficient to observe these differences.

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The forthcoming high- Q^2 experiments designed to investigate color transparency in $(p, 2p)$ [1] and $(e, e'p)$ [2] reactions will also measure the nucleon momentum distribution at much higher energies than any previous experiment. Naively they allow [3] the measurement of the nucleon light-cone density matrix $\rho_A(y, k_t)$ and closely related quantities needed to describe various high-energy phenomena, including the EMC effect and high Q^2 (e, e') reactions.

The aim of this letter is to determine experimental observables sensitive to the qualitative features of the spectral function. In particular we focus on those relevant for the EMC effect.

At high energies the cross section of the $hA \rightarrow h'N_f + (A-1)^*$ reaction can be written as[4]

$$\frac{\frac{d\sigma}{\frac{dp_{h'}}{E_{h'}} \frac{d^3p_{N_f}}{E_{N_f}}}}{2\pi} = \rho_A(p_{res}) \frac{1}{2\pi} \frac{d\sigma}{dt} (s' = (p_{h'} + p_{N_f})^2, t) \frac{[s' - (m_{h'} + m_N)^2]^{1/2} [s' - (m_{h'} - m_N)^2]^{1/2}}{2p_h m_A / A} \quad (1)$$

where $\rho_a(p_{res})$ is the nucleus spectral function, p_{res} is the four momentum of the residual nucleus. Introducing light-cone variables $v_{\pm} = v_0 \pm v_3, v_t$ for the momenta involved (the projectile direction is taken as the 3-axis) and defining $p \equiv p_A - p_{res}$ we can write s' :

$$s' = m_h^2 + m_N^2 + (p^2 - m_N^2) + p_{h+}p_- + p_{h-}p_+ \approx m_h^2 + m_N^2 + p_{h+}p_- \left[1 + \frac{p_+}{p_-} \frac{m_N^2}{p_{h+}^2} + \frac{p^2 - m_N^2}{p_{h+}p_-} \right] \quad (2)$$

The ratio $p_+/p_- \approx 1$ so the second term in the bracket can be neglected. We also find, using the independent-pair approximation, that the small term $(p^2 - m_N^2)/p_{h+}p_-$ is the same for forward and backward moving nucleons. Thus at large energies $s' \approx m_h^2 + m_N^2 + p_{h+}p_-$ so that this reaction probes the dependence of the spectral function on p_{res-} and p_{res_t} but not on p_{res+} . Moreover, in a realistic experimental setup (two

arm spectrometer) the resolution in $(p_A - p_{res})_-$, p_{res}_t remains high at large energies, while the resolution in p_{res}_+ becomes poor [5]. Thus the measurement of the light-cone projection of $P_A(p_{res})$:

$$\rho_A(y, k_t) = \int P_A(p_{res}) \delta(p_{res}_t + k_t) \cdot \delta(y - A(p_A - p_{res})_- / m_A) d^4 p_{res} \quad (3)$$

is possible. Here y is the light-cone fraction carried by the interacting nucleon. The scale is chosen so that y varies between 0 and A .

The quantity $\rho_A(y, k_t)$ is determined from the cross section of Eq. (1) (or from a similar expression for a lepton beam) only if it is a good approximation to neglect final state interactions. The high Q^2 experiments of Refs. 1 and 2 have the specific kinematic advantage that the projectile and final hadron(s) can have only elastic reactions with nucleons in the target. At high energies, forward scattering dominates. Thus elastic interactions can change the transverse component of p_t of the momentum of the projectile and emerging particle(s), but not the plus component. One can estimate the change in the plus-momentum fraction z of the fast particle of momentum p_h in elastic collisions. Applying conservation of momentum and taking the angular distribution to vary as $e^{2/3 t < r_N^2 >}$ lead to the result

$$\delta z \simeq - < t > / (2 p_h m_N) \simeq 1 / (2/3 < r_N^2 > 2 p_h m_N) \simeq 5 \times 10^{-2} \text{ GeV} / p_h, \quad (4)$$

so that δz is proportional to the positive energy loss. Using $< r_N^2 >$ as the square of the electromagnetic radius of the nucleon accounts for the observed forward angular distribution of pp scattering. Thus the change in longitudinal momentum caused by rescattering seems fairly small. If the effects of color transparency were to be observed, δz would be even smaller. Note that the relevant values of p_h can be varied experimentally, so that one can reduce the effects of δz in a controlled manner. Another experimental technique to restrict the effects of final state interactions in hadronic reactions is to constrain the sum of the transverse momenta of the emerging projectile and

knocked out proton to be less than the Fermi momentum. In any case, one expects that the effects of final state interactions are smallest for the lightest nuclear targets. This is not a limitation, since the effects we discuss below are large even for the deuteron.

Even if a particle experiences no change in z as it interacts with the nuclear medium, one generally expects a loss of flux due to absorption into other channels. This absorption effect modifies Eq.(1) by multiplying the quantity $\rho_A(y, k_t)$ by a factor that is essentially independent of y and k_t [6]. We are concerned here with examining a ratio (A of Eq. (12)) of linear combinations of cross sections, and the influence of absorption disappears in such ratios.

We now turn to the prescription used in many papers on the EMC effect, and in most papers on high $Q^2(e, e')$ reactions. This is to identify $P_A(p_{res})$ with the nonrelativistic spectral function

$$P_A(p_{res}) = \langle A | a^\dagger(\vec{p}) \delta(H - p_{res}) a(\vec{p}) | A \rangle \quad (5)$$

normalized as

$$\int P_A(p_{res}) d^4 p_{res} = A. \quad (6)$$

On the other hand the baryon charge of the nucleus is given by [4]

$$\int y P_A(p_{res}) d^4 p_{res} \theta(y) \theta(A - y) = A. \quad (7)$$

Eq. (7) can be derived by considering either the Adler sum rule for deep inelastic scattering off the nucleus, or the matrix element of the baryon current at $q = 0$. The difference between Eqs. (6) and (7) arises from relativistic effects. We use Eq. (7) here since it is a necessary sum rule.

The cross section of deep inelastic scattering off the nucleus is expressed through

$$f_N(y) \equiv 1/A \int y P_A(p_{res}) \delta(y - A(p_A - p_{res})_- / M_A) d^4 p_{res} \quad (8)$$

simply as

$$F_{2A}(x) = A \int f_N(y) F_{2N} \left(\frac{x}{y} \right) dy. \quad (9)$$

In binding/pion models of F_{2A} , the depletion of the F_{2A}/F_{2N} ratio at $x \sim 0.5$ (the EMC effect) is proportional to

$$\eta_\pi \equiv 1 - \int_0^A y f_N(y) dy. \quad (10)$$

The quantity η_π is the light-cone fraction of momentum carried by objects other than nucleons (if the normalization condition (7) is imposed). Calculations [7] using the spectral functions of Ref. [8] lead to $\eta_\pi = 0.034$ which would explain a large fraction of the EMC effect.

The new experimental opportunity to measure ρ_A allows one to make the first direct observation of a non-zero value of η_π from the asymmetry of the y -distribution if the arguments y and $2 - y$ are interchanged. (If $f_N(1 - \delta) = f_N(1 + \delta)$, $\eta_\pi = 0$). Rewriting Eq. (10) using baryon charge conservation (Eq. (7)) and using the upper limit A as either ∞ or 2, we find

$$\eta_\pi = \int_0^\infty (1 - y) f_N(y) dy \simeq \int_0^1 \delta [f_N(1 - \delta) - f_N(1 + \delta)] d\delta. \quad (11)$$

Thus the dominant contribution to η_π must arise from rather large δ . Since the measurements of $hA \rightarrow h'N + (A - 1)^*$ allow the measurement of $f(y)$ directly, we calculate the asymmetry

$$A(\delta) = \frac{f(1 - \delta) - f(1 + \delta)}{[f(1 + \delta) + f(1 - \delta)]/2}. \quad (12)$$

We consider two limiting cases, $A = 2$ and $A = \infty$ (nuclear matter). For $A = 2$ we use the Paris wave function and for nuclear matter we use the spectral function calculated in Ref. [8] and used in the (e, e') reaction [9]. Since the realistic spectral functions of nuclei have about the same dependence on p_{res} and p_{res}^0 for $|p_{res}| \gtrsim 0.3$ GeV/c [10], the results for $A(\delta)$ depend weakly on A for $A > 2$ and for $\delta \gtrsim 0.3$. We

checked that renormalization of nonrelativistic functions $P_A(p_{res})$, $\psi_D^2(k)$ by the factor $m/(m_A - p_{res,0})$ to satisfy the normalization condition (7) leads to a small change of $A(\delta)$ only (though it significantly increases $f(1 \pm \delta)$).

The results are shown in figs. 1 and 2. The models we use predict a large asymmetry which would be easy to observe with measurements performed in the appropriate kinematical regime. (The accuracy of a measurement of $A(\delta)$ is about the same as for the relative measurement of $f(1 \pm \delta)$.) The wiggles displayed in Fig. 2 arise from the discontinuity of the spectral function at the Fermi surface.

We emphasize that a deviation of $A(\delta)$ from 0 is not trivial. In particular, it is straightforward to demonstrate that $A(\delta) = 0$ if the light-cone wave function of the deuteron contains a two-nucleon component only [11]. For heavy nuclei, the application of light-cone quantum mechanics [4] leads to $A(\delta) < 0$ for large δ ($\delta \geq 0.5$) due to contributions of short-range correlations between three or more nucleons. Similarly, one obtains a very small positive $A(\delta)$ for small δ . This occurs even though $\eta_\pi = 0$ within light cone quantum mechanics.

We note that the asymmetry of figs 1 and 2 are of the same sign as that expected from the influence of final state interactions shown in Eq. (4). This could cause a misinterpretation of the results. However, one can check that an experimental measurement of $A(\delta)$ is meaningful by seeing if it changes with Q^2 , choosing a lighter nuclear target or, making a cut on the transverse momentum of the outgoing system.

Another model using conventional nuclear dynamics, closely related to the spectral function model, is the pion model [12,13]. One assumes that the NN -interaction can be described by meson exchanges, and that the nucleons and pions carry the entire momentum of the nucleus. Thus the light-cone fraction carried by nucleons is degraded by the pionic effects and an asymmetry $A(\delta)$ arises.

To estimate $A(\delta)$ in this model one can consider emission of pions as a perturbation,

so that in a first approximation nucleons carry the entire momentum of the nucleus

$$f_N^{(0)}(y) = \int d^3k n_A(k) \delta\left(y - 1 + \frac{k_3}{m_N}\right). \quad (13)$$

The nuclear density $n_A(k)$ is that of Ref. 8. We define $f_\pi(y)$ - the pion light-cone distribution so that

$$n_\pi = \int_0^\infty f_\pi(y) dy \quad (14)$$

is the number of pions, and

$$\eta_\pi = \int_0^\infty y f_\pi(y) dy \quad (15)$$

is the light cone momentum carried by pions. Then

$$f_N(y) = f_N^{(0)}(y)(1 - n_\pi) + \int_y^\infty f_N^{(0)}(z + y) f_\pi(z) dz. \quad (16)$$

This is obtained from the notion that a nucleon carrying a momentum fraction $z + y$ emits a pion of momentum z and ends with y . The sum rules for the total momentum and baryon charge are satisfied by Eq. (16).

To compare Eq. (16) with results of calculation in the first approach we fixed the parameters of the pion model [13] ($R = 0.9$ fm and $g' = 0.6$) to reproduce the result of the first calculation for $\eta_\pi = 0.034$. One can see from figure 2 that this model leads to comparable values of $A(\delta)$.

It is worth remembering that fitting of the EMC effect requires $\eta_\pi \simeq 0.05$ for Fe [4]. If, however, one requires consistency of the model with the Drell-Yan data [14] for the ratio of antiquark distributions in nuclei and deuteron, $\eta_\pi \lesssim 0.015$. Values of η_π in this range can be obtained by changing g' [11,15].

Our calculation indicates that an experiment that could measure $A(\delta)$ with an accuracy of a few percent would be sensitive to values of η_π as low as 0.01.

To summarize, we have demonstrated that forthcoming high Q^2 color transparency experiments would be able at the same time to shed the light on the origin of the EMC

effect, meson degrees of freedom in nuclei, and more generally on relativistic treatments of nuclei.

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Figure Captions

Figure 1. $A(\delta)$ deuteron target.

Figure 2. $A(\delta)$ for nuclear matter. Spectral functions of Ref. 5 solid curve; Nuclear matter pion model dashed curve.

Figure 1

Figure 2