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NUCLEAR PARTON DISTRIBUTIONS AND EXTRACTION OF NEUTRON STRUCTURE FUNCTIONS *

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Abstract

Current information on the nuclear modification of parton distributions is summarized. Implications for the current global analyses of the parton distributions include i) significant increase of d(x)/u(x) ratio at x close to 1 making in close to predictions of perturbative QCD, indications of $\bar{d}(x)$ / $\bar{u}(x)$ > 1 at x=0.007, suggesting that deviation of the Gottfried sum rule from 1/3 is predominantly due to region of very small x. First deep inelastic data of BCDMS at x>1 are also discussed.

INTRODUCTION

Experimental contributions presented at this conference clearly demonstrate, that after many years of measurements the results of different experiments finally agree with each other on a few percent level. Obviously, this greatly simplifies attempts of determining parton distributions in nucleon based on the global analyses of hard phenomena. However many of the key input data are obtained using deuteron targets and, in the case of neutrino scattering, using iron targets. To ensure consistency of the analyzed data samples the deuteron and nuclear data should be corrected for nuclear distortions of the parton distributions. Introducing such corrections seems to be feasible now, since after several years of dedicated experiments (prompted by the observation of the EMC effect) a coherent picture of parton distributions in nuclei seems to emerge. It appears that different physical phenomena are responsible for the observed "zigzag" x-dependence of $R_A(x,Q^2)=F_{2A}(x,Q^2)/F_{2D}(x,Q^2)$: nuclear shadowing provides natural explanation of the small x depletion; deviations of nucleus wave function from the simple many nucleon picture of nucleus are responsible for the dip at x ≈ 0.4-0.7, while increase of R_A at higher x is related to the structure of the short-range correlations in nuclei (for recent detailed review see[1]). In this talk we will consider three examples where nuclear corrections are definitely important: role of nuclear shadowing in determining F_{2n}/F_{2p} ratio at x→0, determination of the d/u ratio at x≥0.5, and quarks in nuclei at x>1.

Small x physics.

It follows from practically model independent analysis of the representation of $F_{2T}(x,Q^2)$ through the commutator $\langle T|J_\mu(y)J_\nu(0)|T\rangle$ that in the $x \to 0$, $q_0 \to \infty$ limit in the nucleus rest frame γ^* converts into a hadronic state at the distances

$$y_3 = 1/2m_N x \gg 2R_A. \qquad (1)$$

In QCD due to color screening the effective interaction cross section, σ, depends on the transverse area, S, occupied by the color:

$$\sigma \sim S, \quad \text{for small } S \qquad (2)$$

and only slowly increases with S for $S > \pi r_\pi^2$. $\sigma_{\gamma^* A(N)}$ can be calculated by applying the Gribov representation for $\gamma^* A$ scattering which is modified in QCD as[2,3]

$$\sigma_{\gamma^* A}(Q^2,\nu) = \qquad (3)$$

$$= \frac{\alpha}{3\pi} \int_0^\infty \frac{R(M^2)M^2\, dM^2}{(M^2+Q^2)^2} \int dS\, \sigma^{(S)}_{\gamma^* M^2 A}(Q^2,\nu)$$

for $x \ll 1/4R_A m_N$. Here M is the mass of the intermediate hadronic state and $R(M^2)=\sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$. $R(M^2) \approx 3\,\Sigma e_q^2$ where sum goes over the flavors which can be produced at given M^2 and it is determined by the quark loop. Contribution of small transverse momenta in the loop corresponds to large color separation: $r_t \sim 1/k_{to}$, and hence to $\sigma_{(q\bar{q})N} \sim \sigma_{\pi N}$, while $q\bar{q}$ pairs with large k_t interact with cross section $\sim \alpha_s^2(k_t^2)/k_t^2$. Neglecting contribution to the shadowing from the $q\bar{q}$ jets with $k_t > k_{to}$ one can calculate nuclear shadowing using eq.2. From comparison with the data for A=1 we find that i) The soft contribution dominates in $F_{2N}(x\sim10^{-2}, Q^2\sim\text{few GeV}^2)$, $\sigma(\bar{q}q, k_{qt}<k_{ot}) \approx (1-0.5)\sigma_{\pi N}$. ii) Color screening which leads to decrease of the cross section $\propto r_t^2$ and hence to the Bjorken scaling at small x is present at least for $r_t^2 < 0.7 r_\pi^2$. Results of the calculations[1-3] which are rather insensitive to the input parameters can be written at x < $1/4R_A m_N$ as[2]

$$A_{eff}/A = (1-\lambda)\ \sigma_{tot}(\pi A)/A\sigma_{tot}(\pi N) + \lambda, \qquad (4)$$

where λ=0.3-0.4. It is rather straightforward to include effects of the finite longitudinal distances (eq.1) for x<0.05-0.1[3], at 0.2> x ≥ 0.0.05 one has to include effects of enhancement of the parton distributions (see next section). Results of calculations agree reasonably well with existing high precision NMC data for μA scattering[4] and the Drell-Yan data for A-dependence of the antiquark distributions[5], see figs.1,2. It rather strongly depends on Q^2 because of scaling violation and absence of shadowing at x≥0.1. Shadowing is expected to be present in all channels - sea, valence quarks, gluons.

Practically all existing calculations of nuclear shadowing at x ≥ 0.01 are explicitly or implicitly based on eq.2. Thus, though details of calculations differ, they lead to similar A-dependence of the shadowing. Therefore if one adjusts parameters of the models to fit the observed shadowing for light nuclei, the predictions of shadowing for the deuteron turn out to be very close. Thus it appears that the shadowing in μD scattering can be estimated with reasonable accuracy (Note that nonlinear effects[6] (parton-parton fusion) which may become significant at smaller x have similar A-dependence and would not affect such extrapolation). We find[7]

$$F_{2D}(x,Q^2)/\{F_{2p}(x,Q^2)+F_{2n}(x,Q^2)\} = 1 - (2.3\pm0.2)\% \text{ at } x < 10^{-2}. \qquad (5)$$

As a result the NMC data[8] at x=0.007 correspond to

$$F_{2n}(0.007)/F_{2p}(0.007) = 1.03\pm0.015\pm0.023,$$

while extrapolation from x=0.08 assuming $\bar{u}=\bar{d}$ leads to 0.94. This estimate indicates that $\bar{d}>\bar{u}$ at small x: $\bar{d}(0.007)/\bar{u}(0.007) \sim 1.1$. Assuming that $x\bar{d}-x\bar{u} \propto x^{0.5-0.7}$ we found deviation of the Gottfried integral from 1/3 observed by NMC (which is somewhat bigger than one given in the paper due to nuclear shadowing effects) is saturated by $\int(\bar{d}-\bar{u})dx$ over the 0<x<0.02 region. The very recent Drell-Yan data[9] implicitly support this conclusion. The authors find no indications of $\bar{d}>\bar{u}$ at x≥ 0.1 on the level predicted in the models where the Gottfried integral is saturated by the contribution to $\int(\bar{d}-\bar{u})dx$ from the region x≥0.1. Thus the only way to reconcile these data with the NMC measurements of the Gottfried integral is to assume that large contribution comes from the x<0.05 region not covered by the Drell-Yan experiment.

ENHANCEMENT OF PARTON DISTRIBUTIONS IN THE X ~ 0.1 REGION

Since parton distributions are shadowed at small x the exact QCD sum rule for the baryon charge

$$\int_0^A \frac{1}{A} V_A(\tilde{x},Q^2)d\tilde{x} - \int_0^1 V_N(x,Q^2)dx = 0, \qquad (6)$$

where $\tilde{x}=AQ^2/2m_A q_0 = Am_N/m_A x$ predicts that valence quark distribution is

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enhanced at higher x. At the same time the exact QCD sum rule for the conservation of the total nucleus momentum implies that gluon and/or sea distribution is enhanced at higher x. Analysis of the data shows that actually the gluons are enhanced though antiquarks are suppressed for all x. This difference of the nuclear effects for valence and for sea quarks, and for gluons makes it impossible to apply universal rescaling of all parton distributions by the same amounts as for F_{2A} ratios.

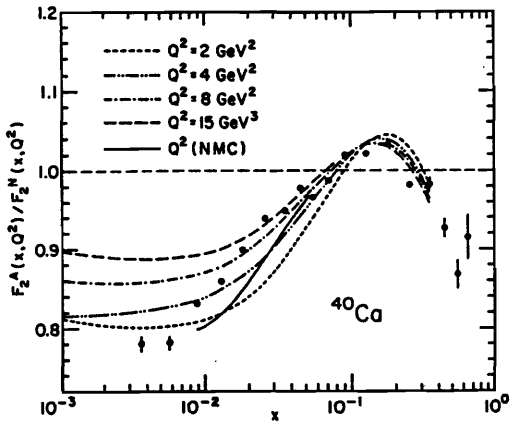

Figure 1. Q^2 - evolution of F_2^{Ca}/F_2^D ratio. NMC data are from [4], curves use [11].

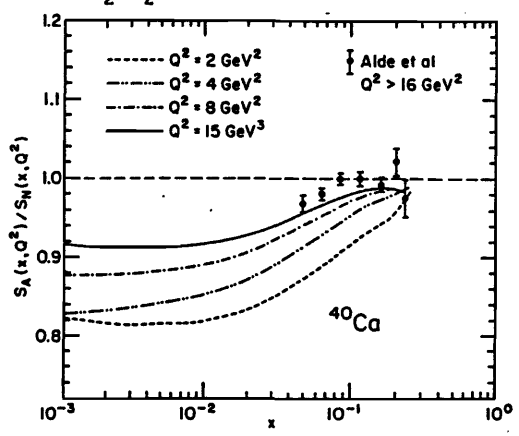

Figure 2. Q^2 - evolution of $\bar{q}_2^{Ca}/\bar{q}_2^D$. The Drell-Yan data are from[5], curves are from[10].

Obviously the shadowing/enhancement pattern noticeably changes the x dependence of the parton distributions in the 0.01<x<0.1 region. For example, in this x-range the ratio F_{3Fe}/F_{3N} decreases as $x^{0.1}$, while it flattens at smaller x. It is necessary to check to what extend this affects the experimental determination of $\int_0^1 F_{3Fe}(x)dx$.

We used the NMC data for Ca for the ratio of the second moments of F_{2Ca} and F_{2D} (which have the smallest relative normalization errors) and the exact momentum sum rule to calculate the ratio of momentum fractions carried by gluons in Ca and in a free nucleon, $\gamma_G(Ca)$[10]. Neglecting the change of the gluon momentum in D and possible change of the strange sea we find using final NMC and SLAC data:

$$\gamma_G(Ca) = (1.4 \pm 0.3 \pm 0.9)\% \qquad (7)$$

By including these effects $\gamma_G(Ca)$ would increase by 0.1-0.5%. Since for small x, $G_A(x,Q^2)$ is expected to be shadowed, the enhancement of $G_A(x,Q^2)$ in nuclei is likely to be concentrated at $x \sim 1/(2m_N r_{NN})$, where $r_{NN} \sim 1$-2 fm is characteristic distance in NN interaction, i.e. 0.03<x<0.15 where it can exceed 10(20)% for A=40(A=∞) and $Q^2 \sim Q_0^2 \sim 1$-2 GeV^2.[10] This gluon enhancement contributes significantly to the scaling violation of the antiquark ratio shown in Fig.2. Therefore small shadowing for q_A observed in Ref.5 for x~0.04 and Q^2>16GeV^2 corresponds to much larger shadowing for $Q^2 \sim Q_0^2$ and same x.

To summarize, all parton distributions are shadowed at small x, while at larger x only valence quark and gluon distributions are enhanced. It is important to take into account this pattern in the global analyses of the data. It is worth noting also that this pattern of nuclear modification of parton distributions is difficult to understand if intermediate range nuclear forces are dominated by exchanges of ordinary mesons.

d(x)/u(x) AT x≥0.45 AND THE EMC EFFECT.

The EMC effect has firmly established that in the region of x<0.8 the nuclear parton distributions are modified in the opposite direction to one expected from the Fermi motion effects. Consequently the currently used procedure [11] for extraction of the $F_{2n}(x)/F_{2p}(x)$ ratio has to be modified to take into account the EMC effect. It was pointed out in [12] that this can be done in a wide region of x in a practically model independent way. Indeed, since essential longitudinal distances, l, (eq.1) for x > 0.2 are smaller than the average internucleon distances and since nuclei are rather dilute systems, any deviations of $R_A(x,Q^2)$ from 1 for x sufficiently below 1 should be proportional to the mean nuclear density $\langle\rho_A(r)\rangle$:

$$R_A(x,Q^2)-1=f(A)\phi(x,Q^2) \qquad (8)$$

where

$$f(A)\sim \langle\rho_A(r)\rangle - \langle\rho_D(r)\rangle \qquad (9)$$

where $\langle\rho_A(r)\rangle = \int\rho_A^2(r)d^3r/A$, and $\int\rho_A(r)d^3r=A$. This estimate is valid for most of the models suggested for the explanation of the EMC effect and it reasonably agrees with the data,[13] see comparison in Refs.2,12,14. This factorisation should break down at x≥0.8 where higher order terms become important in the decomposition in particular for the Fermi motion contribution. As a result for 0.2<x<0.8 we can correct for nuclear effects in the deuteron using data on the EMC effect with heavier nuclei as

$$\frac{F_{2D}(x,Q^2)}{F_{2p}(x,Q^2)+F_{2n}(x,Q^2)} - 1 = \qquad (10)$$

$$= \frac{\langle\rho_D\rangle}{\langle\rho_{Fe}\rangle-\langle\rho_D\rangle}\left[\frac{F_{2Fe}(x,Q^2)}{F_{2D}(x,Q^2)}-1\right]$$

where $\langle\rho_D\rangle/\{\langle\rho_{Fe}\rangle-\langle\rho_D\rangle\} \approx 0.25$. The SLAC analysis[15] has compared values of $R(x)\equiv F_{2n}/F_{2p}$ obtained using preEMC effectprocedure [11] and procedure given by eq.(10). One can see from Fig.3. that results differ qualitatively for x ≥0.5. The new procedure leads to significantly larger value of the ratio, which is consistent with the pQCD estimate of Ref.16, R(x→1)=3/7. Further experiments are necessary to

probe this ratio. The possible options include study of nuclei with similar densities and different n/p ratios, like ^{9}Be, and ^{12}C (S.Rock, private communication), tagged neutron structure function data (l+D $\to l'$+ backward proton +X reaction), the ratio of cross sections of W^+ and W^- production in pp collisions at large y.

SUPERFAST QUARKS IN NUCLEI - x>1.

Measurement of quark distributions at x>1 would enable to study directly the A-dependence and the quark structure of the short-range correlations in nuclei, providing a unique information about properties of small superdense nuclear drops, since the final state interaction does not contribute in the leading twist. Measurements in these kinematics are very difficult due to resolution problems and low cross section - F_{2A} small and decreases with x as exp-bx with b~15. First data at really large 200 > Q^2 > 50 GeV^2 were presented in the contributed paper of BCDMS [17], see Fig.4 where data for highest Q^2 range are presented (according to Ref.17 the data in the highest Q-range have the smallest systematic errors. The analysis required a detailed knowledge of the resolution function of the spectrometer. One of the impressive test was the study of the x>1 events for the scattering off hydrogen, which was found to be described by the detector resolution function without adjustable parameters.Our estimates of the cross section based on the current information about magnitude of short-range correlations in nuclei and the color screening model of the EMC effect agree reasonably with these measurements.

The observed cross section is very small and inclusion of the x>1 region in the evolution equations is likely to have very small effect of the current analysis of the scaling violation.

Natural next step would be to perform detailed measurements using SLAC linac for $Q^2 \in$ (10-20) GeV^2 where leading twist contribution starts to dominate [2], as well as to perform dedicated measurements for $Q^2 \sim$ 100 GeV^2.

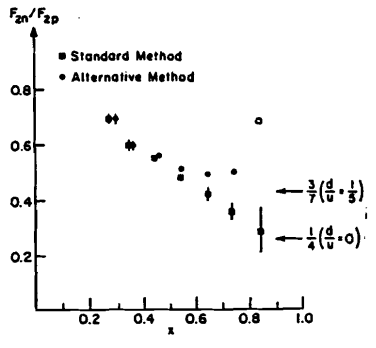

Figure 3. Results of extraction of the F_{2n}/F_{2p} ratio from the F_{2D}/F_{2p} data using "standard method" [11] and Alternative (density method)[12]. Open circle at x=0.85 indicates that the density method is applicable for x<0.8 only.

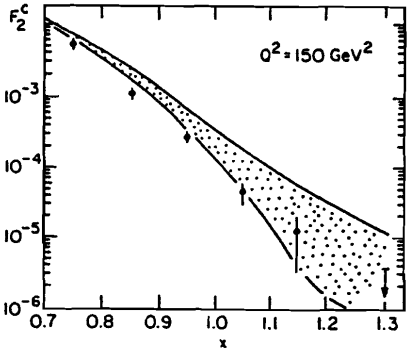

Figure 4. Comparison of the BCDMS data[16] with the model of Ref.3 which takes into account short-range correlations in nuclei and suppression of small size configurations in bound nucleons.

To summarize, inclusion of nuclear effects in the global analyses of parton distribution is clearly necessary. It would lead to a significant modification of these distributions both for large and for small x.

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