Photon parton distributions in nuclei and the EMC effect

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Photons as well as quarks and gluons are constituents of the infinite momentum frame (IMF) wave function of an energetic particle. They are mostly equivalent photons whose amplitude follows from the Lorentz transformation of the particle rest frame Coulomb field into the IMF and from the conservation of the electromagnetic current. We evaluate in a model independent way the dominant photon contribution $\propto \alpha_{em}(Z^2/A^{4/3}) \ln(1/R_A m_N x)$ to the nuclear structure functions as well as the term $\propto \alpha_{em} Z/A$. In addition we show that the definition of x consistent with the exact kinematics of eA scattering (with exact sum rules) works in the same direction as the nucleus field of equivalent photons. Combined, these effects account for the bulk of the EMC effect for $x \leq 0.5$ where Fermi motion effects are small. In particular for these x the hadronic mechanism contribution to the EMC effect does not exceed $\sim 3\%$ for all nuclei. Also the A-dependence of the hadronic mechanism of the EMC effect for x > 0.5 is significantly modified.

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I. INTRODUCTION

Atomic nuclei carry electric charge. Therefore the Coulomb field of a nucleus is a fundamental property of the nucleus in its rest frame. Under the Lorentz transformation to the frame where nucleus has a large momentum, the rest frame nucleus Coulomb field is transformed into the field of equivalent photons. This phenomenon is well known as Fermi - Weizsacker - Williams approximation for the wave function of a rapid projectile with nonzero electric charge [1]. For high energy processes where the photon is off mass, shell this result has been generalized by V. Gribov [2]. Application of these methods allows the evaluation of the role of photon degrees of freedom in the partonic nucleus structure. This effect has practical implications for A-dependence of the EMC effect for $A \geq 50$ nuclei, for the hard processes with the violation of isotopic symmetry in the DIS off protons and neutrons and nuclei. It also gives a non-negligible contribution into extraction of the Weinberg angle from the (anti)neutrino scattering off iron which was performed by the NuTeV experiment at Fermilab, see [3] for a review and references (implications of our finding for this effect will be considered elsewhere). Another effect that modifies the A-dependence of the EMC effect is the difference between the conventional definition of $x = AQ^2/2M_Aq_0$ for the scattering off nuclei which is consistent with the energy momentum conservation sum rule and the one used in experimental papers - $x = Q^2/2m_pq_0$. Combined these two effects result in a strong reduction of the hadronic contribution to the EMC effect for $x \leq 0.5$ where modification of $F_{2A}(x, Q^2)$ due to the nucleon Fermi motion is small.

The photon component of the parton distribution functions of nucleons has been considered for a long time, see for example [4–6]. However the emphasis was on the deep inelastic contribution due to the Q^2 evolution of the quark distributions. In particular the current MRST analysis [7] includes only such contributions neglecting the contribution of equivalent photons to the photon structure function of nucleons, that is, contribution of a photon plus the nucleus ground state.

It has been observed experimentally that nuclear structure functions differ from the sum of structure functions of nucleons. At small x this is the celebrated nuclear shadowing effect predicted within the prequantum chromodynamics (QCD) framework in [8] and evaluated in the leading twist approximation in [9, 10] and observed in a number of experiments, see review in [11]. The observed difference between nucleus structure functions at medium x and the sum of that for free nucleons is known as the EMC effect, for a review see [11]. The presence of the EMC effect requires the presence of non-nucleonic degrees of freedom in nuclei. A natural mechanism is a deformation of the distribution of color within the wave functions of the bound nucleons, for a recent discussion and references see [12]. One of the non-nucleonic effects is the presence of photon degrees of freedom in the light- cone wave function of a nucleus. Note that structure functions of a hadron target are calculable in terms of its light-cone wave functions [13] and their QCD evolution.

The paper is organized as follows. In Section 2 we review the general framework for treating the

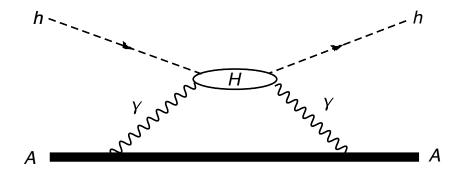


FIG. 1. Diagram for the interaction of photon of the nucleus with a hard probe h

photon field as a a constituent of the parton wave function of the nucleus. In Section 3 we calculate the contribution of the equivalent photons due to the coherent nucleus final state as well as corrections due to the incoherent final states. Numerical results are presented in Section 4 where we also consider another effect contributing to the EMC ratio - proper definition of Bjorken x for the scattering of nuclei that is consistent with the momentum sum rule. We demonstrate that when combined, these two effects account for the bulk of the l EMC effect for $x \leq 0.5$. We also include in the lowest order in k^2/m_N^2 the effect of nucleon Fermi motion which becomes increasingly important with an increase of x at x > 0.5. We conclude that the major "hadronic contribution" to the EMC effect is concentrated at x > 0.5. In Section 5 we outline implications of our analysis for the global fits of nuclear parton distribution functions (pdf's). Our conclusions are presented in Section 6.

II. PHOTON DISTRIBUTION IN HEAVY NUCLEI.

A nucleus is characterized by quark, gluon, photon distributions within a nucleus. To suppress particles production by hard probe from vacuum the gauge condition $A^+ = 0$ is chosen, where A_{μ} is the operator of photon field. In this gauge photon distribution has a form familiar from the parton model; compare Fig. 1. The photon parton distribution can be written as the matrix element of the product of the operators cf. [14]:

$$P_A(x_A, Q^2) = (2\pi x_A p^+)^{-1} \int_{-\infty}^{\infty} dy^- \exp(-ix_A p^+ y^-) 1/2 \sum_{\mu} \langle A | [F_{\mu}^+(0, y^-, 0), F^{\mu, +}(0)] | A \rangle_{A^+ = 0}.$$
(1)

Here $F_{\mu,+}$ is the operator of the strengths of the photon field with transverse component μ , and $x_A = Q^2/2(p_Aq)$ is the Bjorken x for the nuclear target which is the fraction of the nucleus momentum carried by a parton (we will later rescale it by a factor of A to match it more closely to the case of the nucleon target).

A large group of hard processes will probe high energy processes off the nucleus Coulomb field in the

ultraperipheral processes at the LHC[15]. One example of ultraperipheral processes is high energy photon scattering off nucleus(nucleon) Coulomb field with diffractive production of massive lepton pairs $\gamma + A \rightarrow L^+ + L^- + A$. Another process involving photon distribution is the exclusive meson photoproduction off the Coulomb field of the nucleus (the Primakoff effect).

To simplify the calculations it is convenient to represent P_A as the sum of two contributions $P_A = P^{inel} + P_A^{coherent}$. The first term includes nucleus excitations - we will refer to it as the inelastic term. The second term is the contribution of equivalent photons. We will refer to it as the coherent term.

Let us start with a brief discussion of the inelastic contribution. Above we defined it exactly the same way as other parton densities, cf. Eq.1. This definition allows to calculate P_A by evaluating corresponding Feynman diagrams, cf. Fig. 1.

$$x_A P_A^{inel}(x_A, Q^2) = \frac{\alpha_{em}}{\pi} \int d^2k_t \int_{\nu_{min}}^{\nu} \frac{d\nu'}{\nu'} \frac{k_t^2}{(k_t^2 + Q^2\nu'/\nu)^2} F_{2A}(\nu', k_t^2). \tag{2}$$

Here $\nu = 2(pq) = Q^2/x_A$, k_t is the transverse momentum of the photon, and $F_{2A}(\nu, Q^2)$ is the nucleus structure function which does not include the photon field. In the above formulas we neglected the small contribution of the longitudinally polarized photons (F_L^A) . The calculation of the photon structure function accounting for the nucleus excitations is essentially the same as for the QCD evolution of the gluon distribution, cf.[14]. The analogous expression for the photon distribution in protons and neutrons is given in [6].

Account of the photon degrees of freedom requires modification of the QCD evolution equation by including $x_A P_A$ in addition to $x_A G_A$, $x_A V_i$, $x_A S_i$. The presence of the photon component in the nuclear light-cone wave function leads to the modification of the momentum sum rule as follows

$$\int_0^1 \left[x_A V_A(x_A, Q^2) + x_A S_A(x_A, Q^2) + x_A G_A(x_A, Q^2) + x_A P_A(x_A, Q^2) \right] dx_A = 1.$$
 (3)

To remove the kinematic effects it is convenient to redefine the variables by introducing

$$x = Ax_A. (4)$$

leading to

$$\int_0^A \left[(1/A)(xV_A(x,Q^2) + xS_A(x,Q^2) + xG_A(x,Q^2)) + xP_A(x,Q^2) \right] dx = 1.$$
 (5)

We will show that in the case of heavy nuclei the photon distribution in a nucleus cannot be neglected in the evaluation of the EMC effect.

The model for the evaluation of impact of the internucleon electromagnetic interactions (which contribute to the nuclear binding energy term $\propto Z^2/R_A$) into the momentum sum rule for the heavy nucleus target has been suggested in Ref. [18]. The model suggested a relation between the nucleus Coulomb binding energy and the momentum sum rule through the application of the virial theorem in the nucleus

rest frame. So far there exists no model independent derivation of the connection between rest frame Coulomb energy and the momentum sum rule. Their model estimates differ from the well established equivalent photon approximation employed in this paper. Our numerical results are also different.

III. THE CONTRIBUTION OF EQUIVALENT PHOTONS

Here we will calculate the coherent contribution to the parton nucleus distribution that dominates the photon distribution in a nucleus in the leading order in Z. This contribution to $P_A(x, Q^2)$ arises from the interaction of a hard probe with a photon coherently emitted by the target nucleus. The coherent contribution to the photon structure function is unambiguously calculable in terms of the electromagnetic form factors of the nucleus target. In the calculation we neglect by the small contribution of the magnetic form factor of the nucleons which is concentrated at large k_t^2 .

We calculate the field of equivalent photons due to the Lorentz transformation of the familiar nucleus rest frame Coulomb field. To achieve fast track in the calculation of the light-cone nucleus wave function we explore below the relationship between x and the nucleus momentum in the intermediate state. Calculations are simplified in our case since the nucleus is heavy so the static approximation should be sufficiently accurate. In the static approximation zero component of photon momentum in the nucleus rest frame is negligible: $k_0 = k^2/2m_A$. So

$$x = A(k_0 - k_3)/M_A \approx -k_3/m_N.$$
 (6)

The second simplification arises from the observation that the four-vector k can be decomposed over directions defined by external momenta: $k_{\mu} = ap_{\mu} + bq_{\mu} + k_{t}$. Here p is the four-momentum of the target nucleus and q is the four-momentum of the virtual photon (external hard probe) and $(pk_{t}) = (qk_{t}) = 0$. In the essential region: $p_{\mu}A_{\mu,\lambda} \approx (k_{t\mu}/a)A_{\mu,\lambda}$ the essential region, p?A?,? (kt?/a)A?,? [2]. Account of this property leads to the generalization of the Fermi - Weizsacker -Williams expression for the spectrum of the equivalent photons:

$$xP_A^{coherent}(x,Q^2) = \frac{\alpha_{em}}{\pi} \frac{Z^2}{A} \int k_t^2 d^2k_t \frac{F_A^2(k_t^2 + x^2 m_N^2)}{(k_t^2 + x^2 m_N^2)^2},\tag{7}$$

For the characteristic values of k_t^2 in this integral which are determined by the nuclear form factor it is legitimate to neglect the proton form factor. The finite size of the nucleus can be accounted for by the nuclear electric form factor $F_A(t)$, and in our estimates we choose F_A in the exponential form, that is,

$$F_A(k_t^2 + x^2 m_N^2) = \exp(-R_A^2 (k_t^2 + x^2 m_N^2)/6).$$
(8)

Here R_A is the RMS nuclear radius and m_N is the nucleon mass.

Such a form allows one to perform the integration over the transverse momenta of the photons and to calculate the leading logarithmic term in the essential region of small x. We obtain:

$$xP_A^{coherent}(x) = \frac{2\alpha_{em}Z^2}{A}\ln\left(\frac{\sqrt{3}}{R_A m_N x}\right) \exp\left(-\frac{R_A^2 m_N^2 x^2}{3}\right). \tag{9}$$

Note, for completeness, that the contribution of equivalent photons would dominate the nucleus structure function in the limit of fixed x and $Q^2 \to \infty$. This is because the coherent contribution is practically Q^2 independent since form factor of the photon is a slow function of Q^2 due to smallness of α_{em} . In the case of the lightest nuclei the P_A is too small due to the smallness of the electromagnetic coupling constant α_{em} to lead to noticeable effects. In the case of medium and especially heavy nuclei quantity $Z\alpha_{em}$ is not small, so that the photon becomes an important constituent of the light cone wave function of the nucleus.

It is useful to compare different electromagnetic contributions. The most important one is the contribution of equivalent photons in which the fields of individual protons add coherently. This coherence leads to a larger momentum fraction carried by the photon field in nuclei as compared to that carried by individual free protons. Approximate Eq. 9 can be used to evaluate the coherent contribution of the photons to the momentum sum rule:

$$\lambda_{\gamma}^{coherent} = 2\alpha_{em} \frac{Z^2}{A} \int_{0}^{1} dx \ln(\sqrt{3}/x m_N R_A) \exp(-R_A^2 m_N^2 x^2/3) \approx \alpha_{em} \frac{Z^2}{A} \frac{\sqrt{3}}{m_N R_A}.$$
 (10)

Therefore the incoherent contribution to the momentum sum rule $\propto \alpha_{em} Z/A$ can be safely neglected except for the light nuclei.

A direct integration of Eq. 7 leads to

$$\lambda_{\gamma}^{coherent} = \int_0^1 dx x P_{\gamma}(x, Q^2) = \alpha_{em} \frac{Z^2}{A} \frac{1.759}{m_N R_A}.$$
 (11)

which differs from an approximate result of Eq.10 by a factor 1.0156.

In the case of light nuclei we need also to take into account contribution of the incoherent break up of the nucleus. Sum of the two effects can be calculated in the closure approximation where cross section is described by the sum of two diagrams presented in Fig.2 (cf. [16]) and results in replacing

$$Z^2 F_A^2(t) \longrightarrow Z F_N^2(t) + Z(Z-1) F_A^2(t), \tag{12}$$

in Eq.7 (the first and second terms correspond to Fig. 2a, and Fig.2b). Here $F_N(t)$ is the proton electric (Dirac) form factor and $F_A(t)$ is the observed electric form factor of the nucleus which is equal to the product of the nucleus body form factor and $F_N(t)$. The first term in Eq.12 is due to the Coulomb field of the individual protons and it is included in the structure functions of the proton. The contribution of magnetic form factors of neutron and proton is negligible because it is concentrated at -t larger than

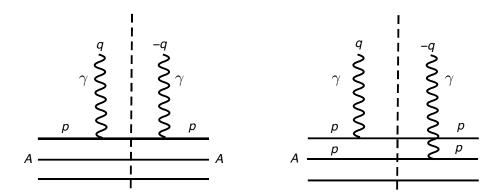


FIG. 2. Diagrams for the photon component of the nucleus including coherent contribution of the whole nucleus and incoherent contributions of the photon fields of individual protons.

the scale of nuclear phenomena. Hence to calculate the additional fraction of the momentum carried by photons in the nuclei we simply need to change Z^2 to Z(Z-1) in Eqs. 7,9 - 11. In particular we obtain

$$\lambda_{\gamma} = \int_{0}^{1} dx x P_{\gamma}(x, Q^{2}) = \alpha_{em} \frac{Z(Z-1)}{A} \frac{1.759}{m_{N} R_{A}}.$$
 (13)

Taking R_A from the compilation of ref.[17] we find

$$\lambda_{\gamma}(^{4}He) = .08\%; \ \lambda_{\gamma}(^{12}C) = .27\%; \ \lambda_{\gamma}(^{27}Al) = .51\%; \lambda_{\gamma}(^{56}Fe) = .84\%; \ \lambda_{\gamma}(^{197}Au) = 1.56\%.$$
 (14)

To evaluate the impact of the presence of the photon component for the nuclear structure functions we can use a reasonable starting approximation: $F_{2A} = ZF_{2p} + (A - Z)F_{2n}$. The small x nuclear shadowing effects modify this approximation, however they are negligible for $x \geq 0.2$ range we are interested in. Since deviations from the additivity are small the effect of the presence of the photons and other "hadronic" effects can be treated as contributing additively to the deviation of the EMC ratio (Eq.15) from one.

IV. IMPLICATIONS FOR THE EMC EFFECT

A. Contribution of equivalent photons

The light-cone momentum carried by the photons is compensated by the loss of the momentum by the nucleons. Since the Coulomb field generated by the protons is soft, it is natural to assume that reduction of the light cone fraction experienced by protons is shared with neutrons due to the internucleon interactions that typically change light cone fractions by a larger amount than the overall change of the light cone fraction due to the photon field. Hence we will assume that the shift is approximately equal for protons and neutrons (an assumption that all shift is due to protons leaving the neutron distribution mostly unchanged leads to a slightly larger EMC effect).

Neglecting other sources of the EMC effect, it is easy to demonstrate that the suppression effect at not too large x can be expressed through the value of the fraction carried by photons as follows

$$R_A(x,Q^2) = \frac{ZF_{2p}(x/(1-\lambda_\gamma),Q^2) + NF_{2n}(x/(1-\lambda_\gamma,Q^2))}{ZF_{2p}(x,Q^2) + NF_{2n}(x,Q^2)}.$$
 (15)

Experimentally the ratio is defined relative to $F_{2^2H}(x,Q^2)$:

$$R_A(x,Q^2) = \frac{F_{2A}(x,Q^2)}{F_{2H}(x,Q^2)}. (16)$$

where factor A in $F_{2A}(x, Q^2)$ is explicitly taken out. Since the Coulomb effect is negligible in the deuteron case we can ignore this difference of the definitions. Also, the SLAC experiment [19] introduced a correction for an unequal number of protons and neutrons. Hence in spite of he uncertainties in this procedure for the sake of comparison with the data it is reasonable to treat nuclei as isoscalar targets.

Using the Taylor series expansion, we obtain

$$R_A(x, Q^2) - 1 = -\frac{\lambda_\gamma x F_N'(x, Q^2)}{F_N(x, Q^2)}. (17)$$

Parameterizing $F_{2p}(x) + F_{2n}(x) \propto (1-x)^n, n \sim 3$ we obtain:

$$R_A^{Coulomb}(x, Q^2) = 1 - \lambda_\gamma \frac{nx}{(1-x)}.$$
 (18)

The results of calculations Eq.18 are presented in the first column of Table 1.

B. Account of kinematics of DIS

Since the EMC effect is small it is legitimate to consider it as the sum of different effects that can be investigated separately. One small but noticeable effect is due to a proper definition of the Bjorken x. In the impulse approximation in case of restriction by the nucleon degrees of freedom in the nucleus wave function one needs to perform comparison of the cross sections for the same x defined in Eq. 4, since this x enters in the convolution formulas for the cross section for the nucleon light-cone fraction α scaled to vary between 0 and A:

$$F_{2A}(x,Q^2) = \int \frac{d\alpha}{\alpha} d^2 p_t F_{2N}(\frac{x}{\alpha}, Q^2) \rho_A^N(\alpha, p_t), \tag{19}$$

where $\rho_A^N(\alpha, p_t)$ is the light-cone density matrix. ρ_A^N satisfies momentum and baryon charge rules which follows from the conservation of energy-momentum and baryon charge, see discussion in [9].

At the same time the experimental data are presented for the same $x_p = Q^2/2m_pq_0$. The ratio

$$x/x_p = Am_p/m_A = (1 + (\epsilon_A - (m_n - m_p)N/A)/m_p), \tag{20}$$

where ϵ_A is the energy binding per nucleon. Using as before the Taylor series expansion we find for the resulting correction for the ratio of nuclear and deuteron cross sections:

$$R_A^{\epsilon} = F_{2A}(x_p)/F_{2^2H}(x_p) = 1 - \frac{nx}{1-x}(\epsilon_A - \epsilon_{2H} - (m_n - m_p)(N-Z)/A)/m_p, \tag{21}$$

We use the observation that in the kinematical region of x < 0.55 Fermi motion effects are a negligible correction and therefore $F_{2A}(x, Q^2) = F_{2N}(x, Q^2)$.

The two effects add as both are small corrections. They lead to the overall contribution to the EMC ratio which is not due to hadronic non-nucleonic degrees of freedom in nuclei

$$R_A(x_p, Q^2) = F_{2A}(x_p) / F_{2^2H}(x_p) = R_A^{\epsilon}(x_p) \cdot R_A^{Coulomb}(x_p).$$
 (22)

C. Comparison with data

The results of the calculation are presented in the first two columns of Table 1. The third and forth columns present the experimental results of [19] and [20]. Results for the carbon and gold targets are also presented as solid curves in Fig. 3.

One can see both from Fig.3 and the Table 1 that the discussed effects change strongly the A-dependence and the strength of the "hadronic mechanism" of the EMC effect. In particular, the difference between the equivalent photon contributions for 12 C and 4 He is comparable to the observed difference between the EMC effect for these two nuclei while the strength of the "hadron mechanism" is at least a factor of $2 \div 3$ smaller for x = 0.5.

The comparison of the calculation with the data at x = 0.6 shows that "the hadronic EMC effect" leads to $R_A(x)$ close to one. Note however that data indicate a significant deviation from a naive expectation of the impulse approximation where $R_A(x) > 1$ for x > 0.5 and growing with increase of x.

Indeed, let us consider the effect of the Fermi motion of the nucleons in nuclei. For moderate $x \le 0.7$ one can write the contribution of this effect to the nucleus/ deuteron ratio as [9]:

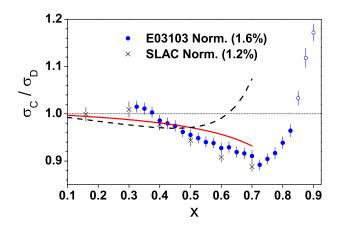
$$R_A(x,Q^2) = 1 + \frac{xF'_{2N}(x,Q^2) + (x^2/2)F''_{2N}(x,Q^2)}{F_{2N}(x,Q^2)} \cdot \frac{2(T_A - T_{2H})}{3m_N},$$
(23)

where T_A is the average nucleon kinetic energy. Taking as before $F_{2N}(x,Q^2) \propto (1-x)^n$ we obtain

$$R_A(x,Q^2) = 1 + \frac{nx(x(n+1)-2)}{(1-x)^2} \cdot \frac{(T_A - T_{2H})}{3m_N}.$$
 (24)

Including this effect using estimates of T_A from [12] as well as the effects we considered before leads to the dashed curves in Fig.3.

One can see from Fig.3 that deviation of the data from the dashed curves grows with increase of x for $x \ge 0.6$ indicating increasing importance of the "hadronic EMC effect". This is consistent with the expectation that suppression of the EMC ratio due to the effect of the suppression of the point-like configurations in bound nucleons should be maximal for quarks that carry a fraction of the light - cone momentum of the bound nucleons close to 1 [9]. Since the Fermi motion effect is $x = T_A$ for x = 0.5, the compensating "hadronic EMC effect" should also be approximately proportional to $x = T_A$. For the realistic nuclear wave functions $x = T_A$ is dominated by the contribution of the short-range $x = T_A$ correlations



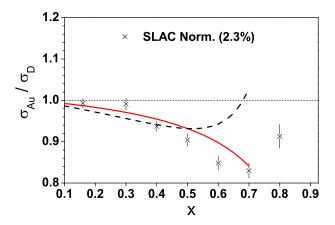


FIG. 3. The solid curve is the contribution to the EMC ration of the nucleus field of equivalent photons and effect of proper definition of x calculated using Eq.22 which is applicable for $x \le 0.7$ only. The dashed curves include also the effect of the Fermi motion estimated using Eq. 24. The data are from [19, 20]. Open circles correspond to W < 2GeV.

TABLE I. The contributions to the EMC ratio for x=0.5, x=0.6 not related to hadronic non-nucleonic degrees of freedom: (a) Coulomb contribution (b) Combined effect of the Coulomb contribution and proper definition of x, (c) the data of [19]. First error is combined statistical and systematic error, the second is the overall normalization error. (d) the data of [20]. First error is statistical, second one is systematic error, the third one is the overall normalization error.

	Eq. (18)	Eq. (22)	[19]	[20]
⁴ He	0.998	0.979	$0.949 \pm 0.016 \pm 2.2\%$	$0.9695 \pm 0.0060 \pm 0.0099 \pm 1.5\%$
$^{12}\mathrm{C}$	0.992	0.971	$0.944 \pm 0.010 \pm 0.7\%$	$0.9553 \pm 0.0050 \pm 0.0106 \pm 1.6\%$
²⁷ Al	0.985	0.962	$0.930 \pm 0.008 \pm 0.7\%$	
$^{56}\mathrm{Fe}$	0.975	0.950	$0.911 \pm 0.007 \pm 1.0\%$	
$^{197}\mathrm{Au}$	0.953	0.932	$0.904 \pm 0.009 \pm 2.3\%$	

 $R_A(x=0.5)$

	Eq. (18)	Eq. (22)	[17]	[18]
⁴ He	0.996	0.968	$0.962\pm0.016\pm2.2\%$	$0.9491 \pm 0.0043 \pm 0.0099 \pm 1.5\%$
¹² C	0.988	0.956	$0.908 \pm 0.007 \pm 0.7\%$	$0.9274 \pm 0.0039 \pm 0.0103 \pm 1.6\%$
²⁷ Al	0.977	0.943	$0.904 \pm 0.007 \pm 0.7\%$	
⁵⁶ Fe	0.962	0.927	$0.874 \pm 0.007 \pm 1.0\%$	
$^{197}\mathrm{Au}$	0.930	0.898	$0.848 \pm 0.008 \pm 2.3\%$	

 $R_A(x = 0.6)$

giving further support to the expectation that modifications of the bound nucleon structure are maximal for the short-range correlations.

Note also that many features of the EMC effect due to the photon field found in the paper are rather similar to the pattern of the pion model of the EMC effect, see discussion of this model in [9]. Thus account of the nucleus photon field puts a stronger limit on the possible contribution to the EMC effect of the suppression of nuclear structure functions due to deformation of the nucleus pion field.

V. IMPLICATIONS FOR GLOBAL NUCLEAR PDF ANALYSES

The observed effects obviously impact on the global analyses of the nuclear pdfs. Here we briefly outline several of the effects.

(a) Correction for the gluon pdfs

All analyses were imposing the momentum sum rule (5) without including the photon field. This leads to an overestimate of the fraction of the momentum carried by gluons. Since the charged partons carry approximately 50% of the momentum of nuclei, the correction for the contribution of the gluons to the

momentum sum rule $\int_0^A 1/Axg_A(x,Q^2)dx$ is $\approx 1-2\lambda_\gamma$. For the case of heavy nuclei, like lead, which are used in the heavy ion collisions experiments, the correction is $\approx 3.3\%$. Half of the effect is accounted for by a rescaling of x by a factor of $(1+\lambda_\gamma)$. The rescaling mostly changes the large x gluon distribution. For small x effect is on the scale of 1%.

(b) Correction for the valence quark pdfs

The current applications of the baryon charge sum rule link the large x suppression of $V_A(x)$ to the enhancement of F_{2A} at $x \sim 0.1$. However the effects we discussed above lead to compensation of the depletion by enhancement at much smaller x where $xV_A(x)$ decreases with decrease of x. This leaves more room for the effect of the leading twist nuclear shadowing which tends to compensate the leading twist shadowing by a corresponding enhancement at $x \sim 0.1$, see discussion in [9].

(c) Correction for the sea quark pdfs

For the case of the antiquark distribution, $x\bar{q}(x) \propto (1-x)^n$, $n \sim 7$ application of Eq.22 leads to a suppression factor for the highest $x \sim 0.2(0.25)$ reached in the Drell-Yan experiments with heavy nuclei of about $R_{\bar{q}} = .96(.95)$ and to even larger effect for the forthcoming Drell - Yan experiment at FNAL.

Overall, it is clear that a new global analysis of the data including discussed effects is necessary.

VI. CONCLUSIONS

We demonstrated that the photon component of the light-cone wave function of the nucleus gives a non-negligible contribution to structure functions of heavy nuclei. Our formula for the photon distribution is a kind of the LO QCD evolution equation and therefore it is exact within the LT approximation, cf. Eq.2. Account for the nucleus photon field leads to a significant EMC effect modifying the A-dependence of the hadronic contribution to the EMC effect. Account of photon field is important for interpretation of both relative strength of the EMC effect for $x \geq 0.5$ - for example ⁴He vs ¹² C, as well as for evaluation of the overall A-dependence of the hadronic mechanism of the EMC effect. We also find a significant modification of the EMC ratio due to a proper definition of the Bjorken x. Combined, the two effects account for most of the EMC effect for $x \leq 0.5 \div 0.6$.

Subtraction of the contribution of photon component of light-cone nuclear wave function slows down the dependence of the EMC effect $[R_A(x) - 1]$ on the atomic number for $x \sim 0.5 \div 0.6$ making it closer to the A dependence of the the probability of short range nucleon correlations in nuclei, and hence more close to the expectations of color screening model of [9] in which radii of quark, gluon orbits in short-range correlations increase with increase of the nucleon momenta.

It is important to perform further experimental measurements of the EMC ratio for $x \ge 0.6$ at large Q^2 which will become feasible at Jlab 12. Especially interesting would be to study the ratio of the EMC effect in 48 Ca and 40 Ca since in this case both effects we consider are practically the same. Moreover such

research would provide a unique window on the structure of neutron rich high density nuclear matter relevant for description of the cores of the neutron stars.

It would be possible to measure small x structure functions of nuclei and therefore photon distributions via Eq. 2 at the LHeC. Our evaluation shows that the most significant contribution to the photon distribution in a nucleus can be accurately evaluated using Eq. 9. At the same time corrections for the incoherent effects maybe included as well, and may lead to significant corrections in the processes with nucleus break up. In particular, this contribution is of relevance for calculating the cross section of ultraperipheral processes where one often considers the cross section summed up over all final nuclear states or even just selects the final states where nucleus was excited [15]. To a first approximation, to treat these contributions it is necessary to modify the standard Weizsacker - Williams formula for the photon flux by replacing the the factor $Z^2F_A^2(t)$ by $Z(Z-1)F_A^2(t)+ZF_N^2(t)$ (a more detailed treatment would involve including also transitions like $N \to \gamma + \Delta$). These issues will be considered elsewhere.

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- $[1] \ E. \ Fermi, \ Z. \ Phys. \ {\bf 29}, \ 315 \ (1924);$
 - C. F. von Weizsacker, Z. Phys. 88, 612 (1934).
 - E. J. Williams, Phys. Rev. 45, 729 (1934).
- [2] V. N. Gribov, "The theory of complex angular momenta: Gribov lectures on theoretical physics," *Cambridge University Press, Cambridge, UK 2003*) 297 p.
- [3] K. S. McFarland [NuTeV Collaboration], AIP Conf. Proc. 655, 68 (2003).
- [4] Y. L. Dokshitzer, D. Diakonov and S. I. Troian, Phys. Rept. 58, 269 (1980).
- [5] M. Gluck, M. Stratmann and W. Vogelsang, Phys. Lett. B 343, 399 (1995).
- [6] M. Gluck, C. Pisano and E. Reya, Phys. Lett. B 540, 75 (2002) [arXiv:hep-ph/0206126].
- [7] A. D. Martin, W. J. Stirling, R. S. Thorne and G. Watt, Phys. Lett. B 652, 292 (2007) [arXiv:0706.0459 [hep-ph]].
- [8] V. N. Gribov, Sov. Phys. JETP 29 (1969) 483 [Zh. Eksp. Teor. Fiz. 56 (1969) 892]; also in V.N. Gribov, Gauge theories and quark connement, Phasis, Moscow, 2002, p. 53.
- [9] L. L.Frankfurt and M. I. Strikman, Phys.Rep. **160**(1988) 235.
- [10] L. Frankfurt and M. Strikman, Nucl. Phys. B 316, 340 (1989), Eur. Phys. J. A 5 (1999) 293.
- [11] M. Arneodo, Phys. Rept. 240, 301 (1994).

- [12] C. Ciofi degli Atti, L. L. Frankfurt, L. P. Kaptari and M. I. Strikman, Phys. Rev. C 76, 055206 (2007) [arXiv:0706.2937 [nucl-th]].
- [13] R. P. Feynman, Photon hadron interactions, W.A. benjamin, Inc., Reading 1972, 282p.
- [14] G. Sterman, An introduction to QUANTUM FIELD THEORY Cambridge, University Press, 1993.
- [15] K. Hencken et al., Phys. Rept. 458, 1 (2008) [arXiv:0706.3356 [nucl-ex]].
- [16] L. Frankfurt, G. A. Miller and M. Strikman, Phys. Rev. D 65, 094015 (2002) [arXiv:hep-ph/0010297].
- [17] I. Angeli, Atomic Data and Nuclear Data Tables, 87, 185 (2004).
- [18] B. L. Birbrair, E. M. Levin and A. G. Shuvaev, Phys. Lett. B 222, 281 (1989).
- [19] J. Gomez et al., Phys. Rev. D 49, 4348 (1994).
- [20] J. Seely et al., Phys. Rev. Lett. 103, 202301 (2009) [arXiv:0904.4448 [nucl-ex]].