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Universality test of short range nucleon-nucleon correlations in nuclei with strange and charmed probes

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Abstract: Understanding the EMC effect and its relation to the short-range nucleon-nucleon correlations (SRC) in nuclei is a major challenge for modern nuclear physics. One of the key aspects of the connection between these phenomena is the universality. The universality states that the SRC is responsible for the EMC effect and that the modification of the partonic structure of the SRC is the same in different nuclei. The flavor dependence of the universality is one of the unanswered questions. The investigations conducted to date have demonstrated the existence and universality of the SRC for light u and d quarks. Recently, it was suggested that the universality for heavy flavors can be studied through their deep subthreshold production in γA and eA collisions. In this paper, we discuss an alternative possibility to access the strange and gluon high-X structure of the SRC and to establish universality for heavy flavors using nuclear semi-inclusive deep inelastic scattering (nSIDIS), which probes different quark flavor combinations depending on the final state hadron. The specific reaction can be "tagged" by observation of a strange or charmed particle registered in coincidence with the scattering lepton. The universality of the SRC can be tested in the kinematic region, i.e., $X>1$, where the contribution to the cross section from SRC becomes dominant. Exploring the strangeness, charmonium, and open charm will shed light on the role of quarks and gluons in nuclei, thereby developing an understanding of how nuclei emerge within QCD.

Keywords: EMC effect, strange and charm quarks in nuclei, short-range nucleon correlation in nuclei

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I. INTRODUCTION

There has been renewed interest in investigating the short-range structure of nuclear matter (see [1, 2] for recent reviews). The traditional nuclear physics considers a nucleus as a collection of proton and neutrons (collectively referred to as nucleons), bound together by their mutual interactions. The mean-field models based on the nucleon-meson picture successfully reproduce the static properties of nuclei as well as the results of lepton- and hadron-nucleus collisions. The effective force that holds the nucleons together stems from fundamental interactions between the constituents of nucleons, which are quarks and gluons. Nevertheless, in the processes occurring at typical inter-nucleon distances of $1.8-2$ fermi, corresponding to the normal nuclear density $\rho_0=0.16\div0.17\ \text{fm}^{-3}$, the underlying quark-gluon structure of nuclear nucleons is hidden. However, both theoretical and experimental studies carried out in the last decades indicate that the conventional nucleon-meson picture of the nucleus is incomplete and unjustified at small distances below 1 fermi.

In commonly accepted meson-nucleon physics, the properties of nuclei are described by the spectral functions $S(k,E_R)$, which represent the joint probability to find a nucleon in a nucleus with momentum k and removal energy E_R. The integration by E_R transforms $S(k,E_R)$ into a function $n(k)$ known as the nucleon momentum distribution of nucleons in the nucleus [3]. This function can be represented as a sum of two components, i.e., $n(k)=n_0(k)+n_1(k)$. The first component, $n_0(k)$, describes the internuclear motion of independent nucleons separated by a distance of $1.8-2$ fermi and extends up to $1\div1.2\ \text{fm}^{-1}$ $(200\div250\,\text{MeV}/c)$, which corresponds to a normal Fermi momentum k_F, while the second component, $n_1(k)$, describes the motion of nucleons with higher momenta. A high momentum component, $n_1(k)$, is generated by the nucleon pairs with small distance between nucleons. These temporary fluctuations in nuclear density are called Short Range Correlations (SRCs) [4]. The nucleon momentum distribution at $k>k_\text{F}$ has universal shape for various nuclei from helium to lead, and follows the power law dependence $n(k)\sim1/k^4$.

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II. BASIC PROPERTIES OF THE SRC

The high momentum correlated part n_1 was investigated in a series of experiments with electron and proton beams. The breakup of the correlated nucleon pairs was studied in $A(e,e'pp)$ and $A(e,e'pn)$ reactions at $Q^2 > 1.3\,\mathrm{GeV}^2$ at JLab [5, 6] as well in double $A(p,2p)X$ and triple $A(p,2pn)X$ coincident experiments at BNL in the initial proton energy region of 6-15 GeV [7, 8]. The results of these experiments reveal that two-nucleon correlations exist in nuclei, accounting for 20%-25% of the nucleons with momentum above k_{F}, with a small center of mass momentum $(k < k_{\mathrm{F}})$ and large relative momentum $(k > k_{\mathrm{F}})$. Up to 600 MeV/c, these correlated pairs are dominated by np pairs of nucleons. Such an excess is understood based on the dominance of the tensor part of the NN interaction at average inter-nucleon separations of approximately 1 fm, which creates predominantly spin-1 isospin-0 neutron-proton SRC pairs [9]. Increasing fraction of pp pairs at higher momenta indicates the transition from an isospin-dependent to an isospin-independent scalar NN interaction (see discussion in [10]). Two additional important properties of correlated nucleons must be highlighted. First, high momentum nucleons belonging to SRC are far from the mass shell and have significant virtuality, expressed as $\upsilon = P^2 - m^2$, where P is the four momentum of the bound nucleon and m is the free nucleon mass. Second, it is believed that a strong repulsive force between nucleons at distances of the nuclear core below 0.5 fermi restrains the size of the nucleon correlation. However, even partial overlapping of the nucleons results in significant enhancing of an average SRC density compared to ρ_0. This is because the density of a nucleon, which is equal to $\rho_N = 1/(4\pi r^3/3) = 0.365\,\mathrm{fm}^{-3}$ ($r \approx 0.85$ fm is a proton electromagnetic radius), exceeds the nuclear saturation density of $\rho_0 = 0.16\,\mathrm{fm}^{-3}$ by a factor of 2.3.

III. EMC EFFECT AND ITS RELATION TO SRC

In 1983, the European Muon Collaboration measured the deep inelastic per nucleon cross section ratio of ^{56}Fe over deuterium [11]. The measured ratio revealed an unexpected structure and became known as the "EMC effect". Plotted as a function of the Bjorken scaling variable $X_{\mathrm{B}} = Q^2/2m\nu$ (Q is four-momentum transfer, ν is energy transfer, and m is the nucleon mass), the ratio showed a linear decrease in the per-nucleon cross section ratio in nuclei relative to deuterium in the range of $0.3 \leqslant X_{\mathrm{B}} \leqslant 0.7$ with very little dependence on Q^2. Such behavior of the ratio was confirmed by subsequent experiments. The observed slope of the linear reduction, commonly referred to as the magnitude of the EMC effect, increases with the nuclear mass, and depends on the local rather than the average nuclear density [12]. This was the first clear evidence showing that the structure function of the bound nucleon differs from that of the free nucleon. These results sparked a lively debate, but there was no general agreement on the origin of the effect. A commonly accepted explanation for the dynamics of EMC effect is still lacking.

The aforementioned similarity of momentum distributions for different nuclei at $k > k_{\mathrm{F}}$ manifests itself as an X_{B}-independent plateau in the per-nucleon quasi elastic cross section ratio of the two nuclei, $a_2(A, X_{\mathrm{B}}) = (\sigma_A/A)/(\sigma_D/2)$. Such behavior of the ratio was first observed at SLAC [13] and subsequently at Jefferson Laboratory [14]. The quantity a_2 usually referred to as SRC scaling factor is interpreted as relative probability for a nucleon to belong to the two-nucleon SRC for the nucleus of mass number A to that for deuteron. The surprising observation of the CLAS Collaboration is that there is a clear linear relation between the magnitude of the EMC effect in the kinematic region $0.3 \leqslant X_{\mathrm{B}} \leqslant 0.7$ and a per-nucleon scaling factor a_2 in the region $1.3 \leqslant X_{\mathrm{B}} < 2$ [15, 16]. This remarkable empirical relation was derived in different theoretical approaches such as the impulse approximation of scattering theory and on the basis of the Effective Field Theory [17]. The observed linear relation indicates that the modification of the nucleon structure is not a mean-field effect but occurs in nucleons belonging to SRC pairs in which the internal structure of the nucleons is briefly modified. This implies that the EMC effect, similar to a short range correlation, is a short distance, high virtuality, and high density phenomenon [1].

IV. MANIFESTATION OF THE QUARK STRUCTURE OF SRC

Recent studies revealed the specific properties of the relation under discussion associated with the isospin structure of the nucleon SRC pairs. It was shown that the per-proton number of the SRC pairs and the strength of EMC effect are linearly correlated, increasing with mass number of neutron-rich heavy nucleus without saturation while the corresponding per-neutron SRC pairs are also linearly related, but saturate remarkably early for nuclei starting from ^{12}C [18]. The dominance of np-pairs at a momentum around 400 MeV/c implies that the absolute value of high momentum protons and neutrons in neutron-rich nuclei are equal. Therefore, on average, protons experience larger EMC effect than neutrons [19]. The existence of an isospin dependent EMC effect means that the in-medium modification for the average u-quarks in the nucleus is larger than that for the d-quarks. These observations support the SRC inspired models of the EMC effect.

The dynamical EMC deviation of the nuclear structure function from nucleon additivity at a fundamental level from QCD degrees of freedom was analyzed in

[20]. The results of the aforementioned experiments performed at JLab and BNL showed that in the momentum range 300-600 MeV/*c,* the SRC of nucleons within nuclei seems to be "isophobic," i.e., proton-proton and neutron-neutron are much less likely to be correlated than proton-neutron pairs. As an explanation of both the EMC and isophobic effects, authors proposed the existence of a novel object inside nuclei named as hexadiquark (HdQ). HdQ is a color singlet combination of six $I=0, J=0[ud]$ strongly bound scalar diquarks with the same quantum number as the ^{4}He nucleus. It was argued that the isophobic SRC are due to the strong QCD interactions of the u and d quarks within the diquark, instead of nucleon-nucleon $n-p$ interactions within the nucleus. According to this model, all nuclei with $A\geq 4$ have an underlying substructure containing one or more strongly bound hexadiquarks. The EMC effect then arises from the lepton scattering on an up or down quark in a diquark entering an hexadiquark. As a crucial test of the explanation of the isophobic nature of both the EMC effect and the SRC, the study of the diffractive dissociation of high energy alpha particles on nuclear targets was proposed in Ref. [21]. Thus, recent theoretical results and experimental observations have provided clear evidence of the QCD effects in nuclei, which manifest themselves in processes occurring at subfermi distances (see [1, 2] for further details).

V. EXTENSION TO THE STRANGE AND CHARM SECTORS

So far, the exploration of the short-range structure of nuclei has been focused on the sector of light quarks. It is of great importance to extend the investigations to the sectors of strange and charm quarks. One of the promising approaches is checking the universality through the study of semi-inclusive deep inelastic lepton scattering on nuclei (nSIDIS) in which the production reaction is "tagged" with a strange or charmed particle. In this case, the relevant variable X can be found from the equation expressing the conservation of energy-momentum, baryonic number, and strangeness/charm in the reaction of the production of strange or charmed hadron h in the interaction of the virtual photon with inter-nuclear target,

$$(P_\gamma+P_T-P_h)^2\geqslant(mX+m_{\rm miss})^2. \tag{1}$$

Here, $P_\gamma(\nu,Q)$, $P_T(mX,0)$, and $P_h(E_h,\boldsymbol{P_h})$ are four-momenta of virtual photon, inter-nuclear target, and produced strange/charmed hadron, respectively; $m_{\rm miss}$ denotes the mass of the lightest particle that has to be produced to meet the conservation laws. In the nucleus rest frame, the variable X is equal to minimal target mass, expressed in nucleon mass m, for which the production of the strange/charm particle with detected parameters is kinematically possible. Note that the Bjorken variable $X_{\rm B}$ can also be interpreted as the minimum target mass in the nucleon mass units.

With the condition of minimal missing mass $m_{\rm miss}$ in reaction, corresponding to the equality of the right- and left-side of Eq. (1), one finds that, for example, in the case of the production of the J/ψ meson with hidden charm,

$$X=(1-z)^{-1}\ [(E_{J/\psi}-(q/\nu)P_{J/\psi}\cos\theta_{qJ/\psi})/m + Q^2/2m\nu-m^2_{J/\psi}/2m\nu], \tag{2}$$

where $E_{J/\psi}$ and $P_{J/\psi}$ are the total energy and three-momentum of produced meson, respectively, ν is the energy transfer from the incoming lepton, $Q^2=-q^2$ is the four-momentum transfer, and m is the nucleon mass. Note also that $z=E_{J/\psi}/\nu$, which is the fraction of the virtual photon energy carried by the J/ψ meson, and $\theta_{qJ/\psi}$ is the angle between $\boldsymbol{q}=\boldsymbol{k}-\boldsymbol{k}'$ ($\boldsymbol{k}$ and $\boldsymbol{k}'$ are three-momentum vectors of incident and scattering leptons, respectively) and $\boldsymbol{P}_{J/\psi}$.

For different species of hadrons, the variable X differs from that defined by Eq. (2) in factors expressing the mass corrections. For the production of hadron h in the interaction of virtual photon with two-nucleon SRC, the magnitude of X changes in the interval $1<X<2$. With increasing energy-momentum transfer ratio, $q/\nu\to 1$, the terms containing the factor $1/2m\nu$ in Eq. (2) can be neglected. Then, the variable X tends to the following simpler expression:

$$X=X_{\rm B}+\alpha_{J/\psi}, \tag{3}$$

i.e., the sum of the Bjorken $X_{\rm B}$ and light cone variable $\alpha_{J/\psi}=(E_{J/\psi}-P^{||}_{J/\psi})/m$ for the J/ψ meson.

Concerning the production of meson pairs with open strangeness or open charm in nSIDIS reactions, the relevant variable X can be found from an equation similar to Eq. (1). For instance, for the K^+K^- pair creation, one has

$$X=(1-z_+-z_-)^{-1}(X_{\rm B}+X_++X\_-M^2_{+-}/2m\nu). \tag{4}$$

Here, $z_+=E_+/\nu$ and $z_-=E_-/\nu$ are the fractions of the virtual photon energy carried by the K^+ and K^- mesons, respectively, $X_{\rm B}$ is the Bjorken variable, X_+ and X_- are X variables for the positively and negatively charged kaons, respectively, and M^2_{+-} denotes the invariant mass squared of the kaon pair. Note that the cross section for nSIDIS reaction depends on both the lepton and hadron kinematic parameters. By identifying the produced hadrons, it is possible to obtain valuable information about the parent strange or charmed quarks from multidimensional analysis of the corresponding production cross section.

The universality is an inherent underlying feature of the connection between the SRC and EMC effects. Universality means that the partonic structure of the SRC is responsible for the EMC effect for all nuclei in the same manner. Regarding light u and d quarks, which are part of nucleons, it was shown that the nuclear structure functions of different nuclei in the EMC region become a universal function once they are appropriately rescaled by the number of SRC pairs [18]. One would expect the existence of universality of the SRC in the production of light mesons such as pion pairs, ρ and ω. However, this has not yet been confirmed experimentally and relevant measurements are highly desirable. Currently, there is no experimental information that such an effect also exists for heavier quarks. It is of great importance to establish the existence of the universality in the strange and charm sectors as well. In particular, the investigation of charmonium ($c\bar{c}$) production in nSIDIS is of special interest as it provides valuable information on the gluon distribution in nucleus, which is completely unexplored. Together with the quark sector, study with the gluonic probe constitutes a crucial test of the universality of the SRC.

The universality suggests the validity of the following relation in the kinematic region $X > 1$, where the hadron production in the interaction of the virtual photon with mean-field nucleons becomes negligibly small and the main contribution to the cross section comes from the interaction with SRC:

$$\begin{aligned} &(\sigma_{\gamma A\to\phi})/(\sigma_{\gamma D\to\phi})\Big|_{X>1.2}\\ &=(\sigma_{\gamma A\to K^+K^-})/(\sigma_{\gamma D\to K^+K^-})\Big|_{X>1.2}\\ &=(\sigma_{\gamma A\to J/\psi})/(\sigma_{\gamma D\to J/\psi})\Big|_{X>1.2}\\ &=(\sigma_{\gamma A\to D^+D^-})/(\sigma_{\gamma D\to D^+D^-})\Big|_{X>1.2}\\ &=(n^A_{\rm SRC}/A)/(n^D_{\rm SRC}/2)\\ &=[F^A_2(X_{\rm B},Q^2)/A]/[F^D_2(X_{\rm B},Q^2)/2]\Big|_{1.4<X_{\rm B}<1.8}, \end{aligned} \tag{5}$$

where $(n^A_{\rm SRC}/A)/(n^D_{\rm SRC}/2)$ is the ratio of the nuclear scaling factors, and $[F^A_2(X_{\rm B},Q^2)/A]/[F^D_2(X_{\rm B},Q^2)/2]$ is the ratio of the structure functions measured in DIS experiments with nuclear targets. Accounting for the center-of-mass motion of the correlated nucleon pair shifts the launch of the universality to $X\approx 1.2$.

In Refs. [22, 23], it was proposed to check the universality through the study of the deep subthreshold production of heavy flavors (J/ψ and Υ) in γA and eA collisions. The aforementioned exploration of strangeness and charm production in nSIDIS reactions beyond the kinematic region allowed for the study of the interaction of the virtual photon with nuclear nucleon carrying the normal Fermi momentum, thereby providing an alternative possibility to establish universality. A common feature of both approaches is that the SRC contribution to the production cross section becomes dominant both at $X > 1$ and at deep subthreshold energies.

Note that the statement expressed by Eq. (5) may be distorted by the effect of the final state interactions (FSI). The role of these interactions in the processes with high energy-momentum transfers presents an unanswered question. Calculations within the Glauber approximation show that in nSIDIS $(e,e'2N)$ reactions for $Q^2 > 1.5\,({\rm GeV}/c)^2$ and $X_{\rm B} > 1$, there exists interaction of secondary nucleons with one another rather than interaction with the nucleons of the nuclear residue $A-2$ [1, 24]. In nSIDIS kinematics at $X > 1$, the flavor of super fast quark (gluon) is "tagged" by detected hadron arising from quark fragmentation. Here, a nucleus serves as an effective femtometer-scale "detector" to probe the propagation, attenuation, and hadronization of colored quarks and gluons. Current experimental estimates of the color lifetime of energetic quarks vary from 2 to 8 fm/c [25, 26], which indicates parton propagation with a small cross section within a distance commensurable with the nucleus size. An analysis of the experimental data on the ratio of the cross sections $\sigma_{pA\to pbar}/\sigma_{pBe\to pbar}$, similar to those in Eq. (5), showed that in the region $X > 1$ the absorption of antiprotons is insignificant in the nucleus up to aluminum, but becomes noticeable in the copper nucleus [26]. This suggests that the FSI effect in nuclei with mass number $A \leqslant 27$ can be neglected. The dependence of the cross section ratios on the lepton and hadronic variables in nSIDIS reactions might help to establish a kinematic range in which the influence of the final state interaction is irrelevant. For example, given that the color lifetime of fast quarks increases with an increase in X [26], an increase in X with an increase in the fraction of energy z transferred to the detected hadrons or hadron pairs in accordance with Eqs. (2) and (4) allows studying the deviation of the ratio (Eq. (5)) from universality by applying the appropriate cuts on z. The high luminosity of nuclear targets $L \approx 10^{37}$ s^{-1}cm^{-2} makes it feasible to test Eq. (5) at the JLab 12 GeV, as well as in future experiments at electron-ion colliders in USA and especially in China (EicC).

VI. CONCLUSION

Although the direct influence of the quark presence in nuclei is now established, a deep understanding of the explicit role of quarks and gluon in nuclei remains elusive. The short-range structure of the nucleus is a largely unknown and almost uninvestigated area of the nuclear physics that calls for more elaborate theoretical calculations, as well as more measurements relevant to the exploration of the SRC and the EMC. One of the key aspects of the connection between these phenomena is the universality of the SRC, which was shown to exist in the sector of light u and d quarks. Recently, it was suggested that the universality of the SRC in the sector of heavy flavors can be studied through the deep subthreshold production of J/ψ and Υ in γA and eA collisions. We propose an alternative possibility to access the strange and gluon high-X structure of the SRC and to establish universality for heavy flavors using nuclear semi-inclusive deep inelastic scattering (nSIDIS), which probes different quark flavor combinations depending on the final state hadron. The proposed extension of the study to strange, charmonium, and charmed hadron production in nSIDIS kinematics at $X > 1$ is expected to shed new light on the genuine structure of SRC. The investigation of the properties of nuclear matter at small distances is of great importance for establishing a complete, femtoscopic picture of the nucleus. Such research will help deepen our understanding of nuclei in the context of QCD. Besides, detailed understanding of short range correlations is necessary for the description of supernova explosions [27] and merging of neutron stars [28] and for interpretation of data on $0\nu2\beta$ decay, neutrino-nucleus interactions, and neutrino oscillations [29, 30].

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