QCD Hidden-Color Hexa-diquark in the Central Core of Nuclei: A Novel Explanation of the EMC Effect

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A central feature of deep inelastic lepton-nucleus scattering is the EMC effect, a distortion of quark distributions within nuclei in the domain $0.3 < x_B < 0.7$, first measured by the European Muon Collaboration in 1983. The CLAS collaboration recently compared nuclear parton distribution functions for a large range of nuclei and confirmed that the EMC effect is dominantly isophobic; i.e., it could be identified with the dynamics of neutron-proton short-range correlations (SRCs) within the nuclear wave function rather than proton-proton or neutron-neutron SRCs. In this article we analyze the EMC deviation of leading twist nuclear structure functions from nucleon additivity directly in terms of the underlying quark and gluon QCD degrees of freedom. We show that an increased number of scalar isospin-0 $|ud⟩$ diquarks within the nuclear wavefunction, relative to free nucleons, provides a natural explanation of the isophobic EMC effect. The primary feature is the formation of a novel color-singlet $|[ud][ud][ud][ud][ud]|$ hexa-diquark state in the nuclear wavefunction. The hexa-diquark state is a charge-2, spin-0, baryon number-4, isospin-0, color singlet state created from 6 strongly bound scalar diquarks. The hexa-diquark may be broken into smaller diquark clusters in the high energy diffractive dissociation of nuclei to final states with multiple color diquark jets. Additional states may be created in the multi-diquark core, e.g., a tetra-diquark with one valence quark, leading to qualitative predictions for the $A = 3$ nuclei targets of the MARATHON experiment.

I. INTRODUCTION

A striking feature of the nuclear structure functions measured in deep inelastic scattering (DIS) is the strong deviation from nucleon additivity observed by the European Muon Collaboration (EMC) at CERN [1] in the kinematic domain of the Bjorken scaling variable $0.3 < x_B < 0.7$. From the nuclear physics perspective, the EMC effect is a direct measure of strong internal nucleon-nucleon dynamical interactions related to short-range correlated (SRC) nucleon pairs within the nucleus [2] rather than a static modification of the nuclear mean field [3, 4]. Nuclear shadowing and anti-shadowing effects are also observed in the nuclear parton distribution functions (PDFs) at low $x_B$, but these effects reflect diffractive processes and the interference of single and multiple scattering amplitudes [5]. The EMC effect is observed in DIS at leading twist, so that the quark structure of the nuclear target is directly measured. In this paper we will analyze the dynamical EMC deviation of nuclear structure functions from nucleon additivity at a fundamental level from QCD degrees of freedom.

In a 2019 paper, the CLAS collaboration analyzed the detailed dependence of the EMC effect on the composition of the nuclear target by systematically comparing nuclei and isotopes with different numbers of protons and neutrons utilizing simultaneous measurements of DIS and quasi-elastic scattering [6]. The physical picture that emerges from their analysis is of high virtuality nucleons in the nucleus fluctuating into strongly interacting SRC pairs, thus distorting their internal quark and gluon structure. The short-range correlations appear to be specifically associated with $n − p$ scattering events versus $n − n$ or $p − p$ interactions within the nuclear domain [6]. This pattern of SRCs has a remarkably strong dependence on the isospin symmetry of nucleon-nucleon interactions. As stated by the CLAS collaboration, the SRC of nucleons within nuclei appear to be ‘isophobic’; i.e., similar nucleons are much less likely to be correlated than dissimilar nucleons, leading to many more neutron - proton SRC pairs than neutron - neutron and proton - proton pairs [7]. Indeed, the neutron-proton correlated pairs are as much as 20 times as
The isospin structure of nucleon-nucleon SRC pairs was first estimated using AGS accelerator data from Brookhaven National Laboratory [10].

The hadronic (and nuclear) eigenstates of the QCD lightfront (LF) Hamiltonian $H_{LF}|\Psi_H\rangle = M_H^2|\Psi_H\rangle$ are built on LF Fock states $|n_H\rangle$, the color-singlet eigenstates of the free LF Hamiltonian $H_{LF}^0$. The coefficients $\langle n|H|\Psi_F\rangle$ in the Fock state expansion for hadrons are the LF wavefunctions $\Psi_F(x_i, k_{i\perp}, \lambda_i)$ which underlie hadronic observables such as form factors, parton distribution functions, transverse momentum dependent distribution (TMDs) and fragmentation functions, and distribution amplitudes [11].

This expansion has led to novel perspectives for the non-perturbative QCD structure of hadrons including the quark-antiquark structure of mesons, the quark-diquark structure of baryons, and the diquark-antidiquark structure of tetraquarks. One such example, the light front holographic QCD (LFHQCD) approach, where the color confining interaction is determined by an underlying superconformal algebraic structure, predicts that the three-quark valence state of the proton has the configuration $|ud[ud]\rangle$ where $|ud\rangle$ is a scalar diquark with color $3C$. LFHQCD gives systematic accounting of observed hadron spectroscopy including the massless pion in the chiral limit. It also predicts supersymmetric 4-plet representations of observed hadron spectroscopy including the massless pion in the chiral limit. It also predicts supersymmetric 4-plet representations of observed hadron spectroscopy.

The presence of the HdQ Fock state, which is strongly bound by the QCD color-confining interactions, can lower the mass of the $^4$He nuclear eigenstate, and thus can account for its exceptionally strong 7 MeV binding energy per nucleon. Each of the 12 quarks in the color-singlet hexa-diquark is labeled by a different spin, isospin, and color. The six strongly bound diquark structures together satisfy the spin-statistics theorem with an overall antisymmetric wavefunction upon interchange of any two quarks. It is thus a significant novel multiquark hadronic state of QCD.

The alpha particle eigenstate of the QCD Hamiltonian can thus be a linear combination of both the HdQ and the conventional four-nucleon bound state of nuclear theory

$$|\alpha\rangle = C_{pmn}|(u[ud])(d[ud])(u[ud])(d[ud])\rangle + C_{HdQ}|(u[ud])(u[ud])(d[ud])(u[ud])\rangle. \quad (3)$$

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The presence of the HdQ Fock state, which is strongly bound by the QCD color-confining interactions, can lower the mass of the $^4$He nuclear eigenstate, and thus can account for its exceptionally strong 7 MeV binding energy per nucleon. Nuclei with $A = 2Z \geq 4$ which can be identified as multi-alpha bound states, such as $^{12}$C and $^{16}$O, have increased binding relative to their neighbours in the nuclear isotope sequences and can have multi-HdQ components. In principle, other heavy nuclei with $A > 4$ can also have both multi-HdQ and nucleon degrees of freedom.
One might expect nuclear HdQ effects to be small as nuclear computations based on the nucleon-nucleon interaction and chiral effective field theory give a reasonable description of binding energies for light nucleons. In fact, recent lattice simulations using effective nucleon degrees of freedom for the ground state properties, binding energies and charge radii were computed for some 70 isotopes from $^3$He to $^{48}$Ca with a typical NLO error of 10% \cite{15}. It would therefore seem that the HdQ contribution to binding energies and charge radii should be less than 10%. However, the $SU(4)$ local scalar interaction (Wigner’s approximate spin-flavor symmetry \cite{16} used in the lattice simulations) has precisely the same effect as the HdQ contribution to the $^4$He \( (p^3p^2n^1n^1) \) state: All quantum numbers are identical: \( Q=2, B=4, I=0, J=0 \). The new $SU(4)$ interaction term in the effective nuclear theory introduced in \cite{15} is equivalent in QCD to adding HdQs.

The actual quantitative determination of the HdQ probability \( \rho_{\text{HdQ}} = |C_{\text{HdQ}}|^2 \) in nuclei with $A \geq 4$ is an important nonperturbative QCD question. Its precise value could, in principle, be answered by lattice gauge theory (LGTH), just as LGTH has recently established the importance of nonperturbative intrinsic heavy quark Fock states in hadrons \cite{17}.

The existence of HdQ configurations in nuclear QCD eigenstates may have a major impact on fundamental nuclear theory. The HdQ configurations provide a novel explanation of the observed isophobic features of the EMC effect at the quark level. The $SU(3)_C$ interactions binding quarks into diquarks allow the formation of the six strongly bound isospin-singlet scalar diquark structures as hidden-color QCD pairings in the nuclear system. In this picture, the quark-diquark model of individual nucleons is modified in the nuclear environment by the formation and pairing of the diquarks.

II. HEXA-DIQUARK CONFIGURATIONS IN NUCLEI AND THE EMC EFFECT

Suppose a $u$ quark struck by the lepton in DIS is in an \[ ud \] diquark. Its light front longitudinal momentum fraction $x$-distribution is modified by the strong interactions with its $d$-quark partner. Similarly, if the lepton scatters on a $d$ quark in a \[ ud \] diquark, its LF $x$-distribution is modified by the strong interactions with its $u$-quark partner. The pairing of valence up and down quarks in conjunction with existing diquarks creates isophobic SRCs at the quark level.

The EMC effect is observed as the difference between the quark PDF distribution $q_A(x, Q)$ measured in DIS on a nucleon vs. the sum of quark distributions obtained from the DIS scattering on the corresponding free nucleons:

$$\Delta q_A = q_A(x, Q) - [Zq_p(x, Q) + (A-Z)q_n(x, Q)]. \quad (4)$$

In this picture, the valence structure of the sum of free nucleons corresponds to $A$ diquarks plus $Z$ up quarks and $A-Z$ down quarks. However, when the nucleons are in the nuclear bound state, these $u$ and $d$ quarks are attracted to each other by the QCD color interaction and form additional \[ ud \] diquarks. The diquarks can combine into the color singlet HdQs.

We postulate that all nuclei with $A \geq 4$ have an underlying substructure containing one or more strongly bound hexa-diquarks. The EMC effect in DIS then arises from the lepton scattering on an up or down quark in an $I = 0, S = 0, Q = \pm 1$ \[ ud \] diquark within the $Q = 2, B = 4$, $I = 0$ hexa-diquark state. The struck up or down quark is strongly correlated with a quark of opposite isospin. The correlation appears as an isophobic short-range correlation.

The difference of the quark distribution $\Delta q_A$ in nuclei vs. free nucleons measured by EMC and CLAS can therefore be attributed to DIS on the quarks of the extra diquarks formed in the nuclear eigenstate. Moreover the quark-diquark SRCs arising from diquark dynamics are automatically isophobic.

III. ADDITIONAL CONSEQUENCES OF THE HEXA-DIQUARK MODEL

We have identified a mechanism based on QCD degrees of freedom that describes the strong isospin dependence of short-range quark-quark correlations. The zero isospin \[ ud \] diquarks in the QCD nuclear eigenstate lead to the isophobic nature of the EMC effect. The key point for nuclear structure is the special role of the color singlet hexa-diquark. It consists of six strongly bound isospin-singlet scalar diquark structures as hidden-color QCD pairings in the nuclear system. In this picture, the quark-diquark model of individual nucleons is modified during nearest neighbor short-range interactions within the nucleus. Scalar diquarks from neighboring nucleons form through QCD interactions with valence up and down quarks, with each nucleon donating one valence quark to their shared diquark. The flavor composition for scalar diquarks requires opposite isospin in order to satisfy the spin-statistics theorem for \[ ud \]. The number of scalar diquarks is maximized for opposite isospin nucleons, i.e., interactions occur predominantly between neutrons and protons rather than neutron-neutron or proton-proton (the definition of “isophobic”). Thus the zero isospin of the HdQ also leads to isophobic SRC nucleon-nucleon correlations in nuclei.

Diquarks can condense into an energetically favorable six-unit color-singlet Fock state, the hexa-diquark, in a possible analog to a color superconducting state \cite{18}. The HdQ component within the $^4$He nuclear wavefunction may play a crucial role in lowering its mass. Diquarks can form through attractive $SU(3)_C$ interactions and diquarks themselves can bind together leading to the hexa-diquark with the spin-color structure \cite{11}, the first viable multi-diquark state with the necessary spin-statistics with respect to its constituents. It is the twelve quark color singlet manifestation of “hidden color” \cite{15} in the nuclear system.

Several questions are raised by the scalar hexa-diquark model.

1. Does this explanation for the EMC effect imply it is identical for $u$ and $d$ type quarks?

The effect is identical for $u$ and $d$ type quarks. We have not given a special role to the specific $u$ and $d$ coupling to the virtual photon in the DIS sequence for the formation of the intermediate HdQ state. Therefore the basic mechanism would not
depend on the $u$ or $d$ active quark; however the specific composition of the debris in the final state would depend on the $u$ or $d$ coupling. Nuclei with $Z < \frac{A}{3}$, i.e., those with more neutrons than protons as is the case for the majority, will therefore appear to interact more frequently with up quarks. However the HdQ treats both $u$ and $d$ on the same footing.

2. Does the model imply there is an EMC effect for sea quarks?

A thorough exploration of the multiquark dynamics would be required to answer this question more precisely. As discussed earlier, we do expect larger repulsive forces at the core from multiquarks, which would exceed the larger distance confinement pressure from gluons [19]. Therefore the effects from higher Fock components would likely be decoupled as compared to the valence contribution of the intermediate hexa-diquark.

3. Does the EMC effect depend on the target polarization?

The model proposed is isospin dependent and in fact is isophobic. Therefore even for $n$-$p$ pairs there is an important dependence on the singlet or triplet configuration of the pair. One could devise a polarization experiment which could address this critical prediction of the model.

4. Is the EMC effect the same for DIS charge current ($i.e.,$ neutrino beam) vs. neutral current reactions?

The equivalent DIS sequence for the charged current amounts to replacing the $\gamma^*$ by a $W$ spin-1 vector boson [1], and since the $W$ has no isospin assignment we would expect similar processes as the sequence initiated by an isospin-0, $J=1$ photon.

**IV. CONCLUSIONS**

In summary, we have identified a novel color-singlet multiquark state, the hexa-diquark, which mixes with nuclear states with $A \geq 4$ and may underlie the phenomena of isosbolic SRCs. It has zero internal orbital angular momentum, $J = 0$, zero radial quantum number $n = 0$, obeys Fermi-statistics, and has maximal QCD binding. One or more hexadiquarks should be an important degree of freedom of heavy nuclei. The difference between leading twist nuclear and nucleon structure functions in Eq. [4] is sensitive to the difference of $[ud]$ diquarks in nuclei vs. nucleons, and thus the isosbolic EMC effect is also sensitive to the HdQ correlations within the QCD nuclear eigenstates. One can test this explanation by diffractively dissociating relativistic beams of heavy nuclei. The final state should display the underlying hexa-diquark composition of the nucleus [14].

The HdQ allows an important sharing of momentum between the $u$ and $d$ valence quark pairing in nearest neighbor neutrons and protons leading to the subsequent ejection of the proton and neutron in the SRC pair. A key aspect of the model is its isospin structure which gives a strong isospin dependence to the correlated pairs. Further study of the equilibrium dynamics in multiquark systems and possible DIS polarization experiments would be required to affirm the validity of the proposal presented here. As a corollary, the MARATHON experiment at Jefferson Lab [20] with $^3$He and $^3$H targets should not exhibit strong isosbolic SRCs as the hexa-diquark cannot form in such nuclei. Despite this, scalar $[ud]$ diquarks can form via SRCs even in the lightest nuclei. They will not form color singlets in the way that the $^4$He nucleus allows for because of spin-statistics constraints on the wavefunction. An important example of this is the diquark model applied to deuterium, which creates an overall symmetric wavefunction with respect to its quark constituents and is therefore disallowed. We do expect isosbolic SRC in the lightest nuclei at a suppressed level as they may contain one or more central diquarks (e.g. one $[ud]$ for a single nucleon, two for the deuteron, and three for the $A = 3$ nuclei). Any nuclei with $A > 3$ is predicted to contain the hexa-diquark in its Fock space and will therefore exhibit strong isosbolic SRC, a further investigation of which we defer to a future work [21].

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