Diquark Induced Nucleon-Nucleon Correlations and the EMC Effect

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Diquarks formed from valence quarks across a nucleon-nucleon pair are predicted to affect physical phenomena on vastly different scales, from nuclei to neutron stars. On nuclear distance scales, diquark formation is proposed as the underlying cause of nucleon structure function distorting interactions in all nuclei. Diquarks in this model form in the $3C \otimes 3C \rightarrow 3C$ channel of SU(3)$_C$ acting on the valence quarks of nearest neighbor nucleons, creating a short-range correlation between nucleon pairs. The most energetically favorable diquark configuration is a valence $u$ quark from one nucleon with a valence $d$ quark from the other in a spin-0 state bound together via single gluon exchange and an attractive quantum chromodynamics short-range potential. Formation of a new scalar isospin singlet $[ud]$ diquark across a N-N pair is proposed as the primary QCD-level theoretical foundation for short-range nucleon-nucleon correlation models of distorted structure functions in $A \geq 3$ nuclei.

Contributions from the higher mass spin-1 isospin triplet states $(ud)$, $(uu)$ and $(dd)$ are possible, with the spin-1 $(ud)$ diquark proposed as a weak but viable structure function distortion mechanism for the spin-1 ground state deuteron. Diquark induced short-range correlation predictions are made for lepton scattering experiments on $^3$H and $^3$He nuclear targets, with novel implications for the coefficients of the 3-valence quark Fock states in the nucleon wavefunction.

I. INTRODUCTION

Diquarks are quark-quark bonds formed at short separation distances and in high pressure environments [1–3]. In this work, diquark formation across two nucleons via an attractive quantum chromodynamics (QCD) quark-quark potential is proposed as the underlying QCD-level source of short-range correlations in nuclear matter and, furthermore, the cause of distortions in quark behavior in the nuclear environment.

Strong evidence for short-range nucleon-nucleon correlations as a source of distortions of measured nucleon structure functions when bound in nuclei has been found by the CLAS collaboration [4]. Theoretical models of structure function modifications have been studied since the European Muon Collaboration’s deep inelastic scattering (DIS) experiments at CERN first revealed the surprising distortions now known as the EMC effect in 1983 [5]. Two leading explanations for the EMC effect have emerged over time: multi-nucleon mean field models [6, 7] and the 2-body nucleon-nucleon short range correlation (SRC) model [8, 9]. A QCD model for short range nucleon-nucleon correlations in all nuclei is given in this work, based upon the strong binding energy of spin anti-aligned valence up and down quarks in neighboring nucleons. For neighboring nucleons with sufficient wavefunction separation distance, $u$ and $d$ quarks with opposite spins are predicted to form a new scalar diquark via the attractive potential of the antisymmetric SU(3)$_C$ channel $3C \times 3C \rightarrow 3C$. The triplet set of isospin-1 spin-1 diquarks can also contribute to this effect, in particular in the deuteron nucleus (Sec.VI), but their higher masses suppress their contributions to ground state wavefunctions.

The wavefunction of the nucleon-nucleon (N-N) system with the newly formed diquark is no longer a state of two color singlets but a mixed state which may contain from one to three diquarks. Color-charged scalar diquarks may take on the role of Cooper pairs in U(1)$_{EM}$, potentially breaking SU(3)$_C$ symmetry by their formation in a two nucleon system [10]. The maximal scalar diquark formation is the tri-diquark state $[ud][ud][ud]$, a 6-quark object that is suppressed from combining into a $J=0$ color singlet due to spin-statistics constraints on the di-nucleon system. This is relevant for the deuteron wavefunction, allowing for spin-1 vector diquark induced structure function distortions as discussed in Sec.VI.

The deuteron is an anomalous case in the diquark formation model due to the color confinement constraint on the $n-p$ system; there is no external nuclear medium for QCD diquarks in $^2$H to move through. The idea of diquarks as Cooper pairs dates back to the earliest days of color superconductivity [11], not long after the formulation of SU(3)$_C$ [12], and has been well-studied since then [13–15] including as a delocalized quark-gluon solution to the EMC effect [16].

A 12-quark color-singlet solution to the EMC effect has recently been published, a 6-diquark state dubbed the “hexadiquark,” proposed to modify structure functions for the $^4$He nucleus and all $A \geq 4$ nuclei [17]. The diquark formation model presented in this work acts twice within the hexadiquark and in addition, occurs in every N-N pair, includes the isospin triplet diquarks and must be present in $A = 3$ nuclei.

The MARATHON experiment at Jefferson Lab [18–20] is expected to publish EMC effect results in the near future. The E12-11-112 experiment at Jefferson Lab with $A = 3$ nuclear targets is expected to have isospin dependent SRC results in the near future. Predictions for $^3$He and $^3$H data from the diquark formation model are given in Sec.V.

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II. N-N DIQUARK FORMATION MODEL

Diquark formation across a pair of nearest neighbor nucleons is based on the following three criteria:

- Quark-quark coupling: Viability of the $3_C \otimes 3_C \rightarrow \overline{3}_C$ channel of QCD
- Quark-quark potential: $V(r_{q-q})$ attractive and binding at short distances
- Diquark binding energy: Much greater than average nuclear binding energy

The first two criteria are well-known calculations applied in a novel setting, i.e. across the N-N pair. The third criterion, diquark binding energy, is calculated in Sec.III. Auxiliary arguments in support of diquark formation are also included within this work, e.g. in the quark-quark separation distance estimates of Sec.IV.

Diquark bonds, or correlations, are a viable QCD combination of two quarks each in the fundamental representation of SU(3)$_C$ transformed into an antifundamental representation, $3_C \otimes 3_C \rightarrow \overline{3}_C$. The quarks in a diquark are continually exchanging single gluons for the duration of the bond.

Diquark formation utilizes the attractive potential between two quarks in the fundamental representation of SU(3)$_C$, calculated to have exactly half the strength of a color singlet $3C \otimes 3C \rightarrow 1C$ potential [21, 22],

$$V(r) = \frac{2}{3} \frac{g_s^2}{4\pi r},$$

where $g_s$ is the QCD coupling, to create a quark-quark bond between a pair of nearest neighbor nucleons. The binding energy of the diquark is calculated in Sec.III.

Estimations of the nucleon-nucleon separation distance sufficient for diquark formation are in Sec.IV. An upper limit distance scale for $V(r_{q-q})$ is taken to be the separation between the centers of masses of adjacent (and in contact) nucleons. For a proton charge radius of $r_p = 0.84$ fm [23–26] and a neutron magnetic radius of $r_n = 0.86$ fm [27], this gives a rough estimate for in-contact but non-overlapping N-N of $d_{NN} < 1.72$ fm.

For nucleons with high enough relative momenta $\Delta_{PN-N}$, the distance between nearest neighbor nucleons becomes smaller than the diameter of the nucleon [28], roughly for $\Delta_{PN-N} \gtrsim 300$ MeV/c, a momentum value above the nuclear Fermi momentum of $k_F \approx 2m_n \approx 250$ MeV/c/c [29]. In nuclei, quantum fluctuations in the spatial separation between neighboring nucleons have been proposed to achieve sub-nucleon diameter overlap with densities up to 4 times larger than typical nuclear densities [30], but such fluctuations are not necessary for this model. The quark-quark potential acts to correlate neighboring nucleons and may even replace the need for quantum fluctuations in N-N separation distance to form SRC.

The lowest mass [ud] diquark combines the SU(3)$_C$ triplet up and down flavor quarks in isospin singlet and spin singlet states to form an overall antisymmetric wavefunction upon exchange of quarks,

$$|\psi_{(ud)}(r)|^a = \frac{1}{2} \epsilon_{abc} d^b_c u^+_c d^+_b u^+_d d^+_c u^+_d,$$

where the exchange symmetry follows each representation (color, flavor, spin) and is either symmetric or antisymmetric denoted by $A$ or $S$. Thus the most energetically favorable configuration of the diquark is the $|ud\rangle$ state. The spin-1 isospin-1 diquark $(ud)$ will also be available as a binding mechanism between nucleons, despite its higher mass, as will the $(uu)$ and $(dd)$ isospin-1 triplet companions. Formation of any of these diquarks will contribute to the observed distortions of quark distribution function in nuclei. Here the primary focus is on the most energetically favorable state, $|ud\rangle$.

In the quark-diquark model of baryons the only nucleon pairs with available $u$ and $d$ valence quarks are proton-neutron pairs. In this scenario, diquark induced short-range correlations between nucleons are strongest for the proton-neutron system with the neutron given by $|d(ud)|$ and the proton $|u[ud]|$, a conclusion strongly supporting $n-p$ SRC as the EMC effect mechanism. Experimental results indicate that $n-p$ correlations are up to $\approx 20$ times stronger than $n-n$ or $p-p$ [29, 31] for relative N-N momenta of $300-650$ MeV/c.

In the 3-valence quark internal configuration of baryons, formation of a $|ud\rangle$ scalar diquark will not be restricted to $n-p$ pairs. The quark flavors of both $n-n$ and $p-p$ pairs allow diquark induced short-range correlations to form. Neutron-proton pairings are still favored because there are more $|ud\rangle$ combinations possible from the $n-p$ system than from $p-p$ or $n-n$, shown explicitly in Sec.V. The ratio of $|ud\rangle$ combinations in $n-n$ or $p-p$ vs. $n-p$ when nucleons have a 3-valence quark internal configuration is readily distinguished from the mandatory $n-p$ correlations of the quark-diquark configuration of nucleons.

This argument can be used to probe the internal configuration of valence quarks in nucleons over the EMC effect experimental parameter space. If scalar $|ud\rangle$ diquark formation is the underlying QCD model of the distortion of nucleon structure functions, then any experimental result showing only neutron-proton N-N short-range interactions indicates a predominantly quark-diquark nucleon structure in the corresponding physical

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1 Estimated from the masses of $\Delta$ baryons and $N$ nucleons; e.g. for the $S = \frac{1}{2}$ baryon $\Delta^3$ with quark content $(ud)d$ and the $S = \frac{3}{2}$ quark content $[ud]d$ neutron, $m_{(ud)} - m_{[ud]} \approx \frac{2}{3} (M_{\Delta^3} - M_N) \approx 200$ MeV. Square brackets denote scalar diquarks and parentheses denote the spin-1 vector diquarks.
III. DIQUARK BINDING ENERGY

The masses and binding energies of diquarks formed from u and d quarks may be calculated using a simple but powerful model of baryon and meson masses with sub-hadronic hyperfine interactions [34].

\[
M_{\text{baryon}} = \sum_{i=1}^{3} m_i + a^b \sum_{i<j} (\bar{\sigma}_i \cdot \bar{\sigma}_j) / m_i m_j, \tag{4}
\]

\[
M_{\text{meson}} = m_1 + m_2 + a^m (\bar{\sigma}_1 \cdot \bar{\sigma}_2) / m_1 m_2, \tag{5}
\]

with \( a^b \) a free parameter that is fit to baryon data and \( a^m \) a free parameter fit to meson data.

The effective masses of the light quarks in baryons are found using Eq. 4 and fitting to measured baryon masses,

\[
m_u^b = m_d^b = m_s^b = 363 \, \text{MeV}, \quad m_u^b = 538 \, \text{MeV}, \tag{6}
\]

with average error \( \Delta m_d = 5 \, \text{MeV} \) when compared to measured ground state baryon masses [34, 35]. These are effective masses of quarks bound in hadrons [36], not Standard Model Lagrangian masses where lattice QCD calculations give average u and d quark masses in the MS renormalization scheme evaluated at energy scale 2 \( \text{GeV} \) as \( m_{\text{MS}u,d} = (3.9 \pm 0.3) \, \text{MeV} \) [37] and \( m_s = (92.47 \pm 0.69) \, \text{MeV} \) [38].

For diquarks consisting of u and d quarks, diquark parameters are calculated using the ground state masses of the spin-\( \frac{3}{2} \) isospin-0 \( \Lambda(1116) \) and the spin-\( \frac{1}{2} \) isospin-1 \( \Sigma^0(1193) \) baryons [26]. Both baryons have quark flavor content \( uds \) but differ by the spin and isospin assignments of their u and d quarks. Their mass splittings imply that the \( \Lambda(1116) \) baryon contains the spin-0 isospin-0 \( [ud] \) diquark and \( \Sigma^0(1193) \) the spin-1 isospin-1 \( [ud] \) diquark.

Using the parameters from Eq. 6 and Table II, the scalar \([ud]\) diquark binding energy is found to be

\[
\text{B.E.}_{[ud]} = m_u^b + m_d^b + m_s^b - M_\Lambda = 148 \pm 9 \, \text{MeV}. \tag{7}
\]

where the spin coupling between the \([ud]\) diquark and the s quark is zero due to the cancellation between u–s spin coupling and d–s spin coupling.

The \([ud]\) diquark mass then follows,

\[
m_{[ud]} = m_u^b + m_d^b - \text{B.E.}_{[ud]} = 578 \pm 11 \, \text{MeV}. \tag{8}
\]

| Diquark | Binding Energy (MeV) | Mass (MeV) | Isospin | Spin |
|---------|---------------------|------------|---------|-------|
| [ud]    | 148 ± 9             | 578 ± 11   | 0       | 0     |
| (uu)    | 0                   | 776 ± 11   | 1       | 1     |
| (dd)    | 0                   | 776 ± 11   | 1       | 1     |

Uncertainties calculated using average light quark mass errors

\[ \Delta m_q = 5 \, \text{MeV} \] [35]

In order to estimate the masses of the vector diquarks, Eq. 8 cannot be used because of the spin-spin interaction between the valence s quark and the spin-1 diquark constituents (the interactions which canceled to zero for the \([ud]\) diquark). Explicitly, the sub-hadronic hyperfine energies are given by

\[
\Delta E_{\text{HFS}} = \int \frac{-3a/m_u^2}{a/m_u^2 - 4a/m_u m_s} \frac{1}{(\Sigma^0)^2} \tag{9}
\]

with free parameter \( a \) fit to data, \( a / (m_u^2)^2 = 50 \, \text{MeV}, \) and \( q = u, d [34, 35] \). The mass of the \((ud)\) diquark can be found by using the 2-body meson mass formula instead,

\[
M_{(ud)} = m_d + m_u + a (\bar{\sigma}_1 \cdot \bar{\sigma}_2) / m_1 m_2 \tag{10}
\]

where \( \bar{\sigma}_1 \cdot \bar{\sigma}_2 = +1 \) for \( S = 1 \), giving \( m_{(ud)} = 776 \, \text{MeV} \).

The masses of \((uu)\) and \((dd)\) are the same as the \((ud)\) in the approximation of \( m_u = m_d \).

Binding energies for vector diquarks cannot be calculated using Eq. 7 (with the appropriate baryons) because of spin-spin interactions that occur between the spin-1 diquark constituents and the remaining valence quark. More to the point, isolated vector diquarks do not have binding energies because aligned spins add mass to the system, in the case of the \( \Sigma \) baryons \( \sim 50 \, \text{MeV} \). However, there can be spin interactions between the vector diquark and the valence quarks in either nucleon of the correlated pair that lower the energy of the N-N system. The combined binding energy of vector diquarks and valence s quarks is given here as an example of this effect, but the assumption in this work is that the \( S = I = 1 \) diquarks are not required to couple to other spins and therefore \( B.E.(qq) = 0 \).

The combined binding energy of the spin-1 isospin-1 \((ud)\) diquark and the s quark is found to be half that of the scalar diquark,

\[
B.E._{(uu)s} = m_u^b + m_d^b + m_s^b - M_{\Sigma^0} = 71 \pm 9 \, \text{MeV}(11)
\]

The combined binding energies of the remaining isospin triplet spin-1 diquarks \((uu)\) and \((dd)\) with the valence s quark are found using the \( \Sigma^- (1197) \) baryon, quark content \( dds \) and the \( \Sigma^+ (1189) \) baryon, quark content \( uus \),

\[
B.E._{(uu)s} = m_u^b + m_d^b + m_s^b - M_{\Sigma^-} = 75 \pm 9 \, \text{MeV}(12)
\]

and similarly for \( B.E._{(dd)s} = 67 \pm 9 \, \text{MeV} \).

Diquark parameter results are listed in Table I with relevant baryon parameters listed in Table II.
TABLE II: Relevant SU(3)_C hyperfine structure baryons [26]

| Baryon | Diquark-Quark content | Mass (MeV) | \( I\left(J^{P}\right)\) |
|--------|------------------------|------------|------------------|
| \(\Lambda\) | [ud]s | 1115.683 ± 0.006 | 0 (\(\frac{1}{2}^+\)) |
| \(\Sigma^+\) | (uus)s | 1189.37 ± 0.07 | 1 (\(\frac{1}{2}^+\)) |
| \(\Sigma^0\) | (ud)s | 1192.642 ± 0.024 | 1 (\(\frac{1}{2}^+\)) |
| \(\Sigma^-\) | (dd)s | 1197.449 ± 0.030 | 1 (\(\frac{1}{2}^+\)) |

\(I\left(J^{P}\right)\) denotes the usual isospin \(I\), total spin \(J\) and parity \(P\) quantum numbers, all have \(L=0\) therefore \(J = S\).

The conclusion of the diquark parameter calculations is that a pair of nucleons in close proximity such that their valence quarks sense the attractive \(3C \times 3C \to \bar{3}C\) SU(3)_C channel can lower their energy significantly by forming a bound scalar [ud] diquark.

IV. DIQUARK SEPARATION DISTANCE

From the binding energy calculation in Sec.III, the diquark separation distance may be estimated with the method used for the deuteron radius calculation as well as for other bound state radii [39]. The relationship between the binding energy of a composite object and the radius of the object is given by

\[
R = \left(\frac{\ln(2)}{2\mu B}\right)^{1/2}
\]

where \(B\) is the binding energy between the two bodies, here given by 148 MeV for the scalar diquark, and \(\mu\) is the reduced mass of the two body system, given by \(\mu = \frac{m_u m_d}{m_u + m_d}\) \(\sim 181\) MeV. Using the values calculated in Sec.III, the radius of the scalar [ud] diquark is estimated to be

\[
R_{[ud]} \sim 0.6 \times 10^{-15}\text{ m.}
\]

An earlier study of the spatial structure of diquark Cooper pairs in a color superconductor estimated a separation distance between quarks in a diquark from \(d_{q-q} \approx 1.2\) fm to \(d_{q-q} \approx 0.5\) fm by solving the Fermi gap equation and calculating quark-quark coherence lengths. The value found here is at the upper end of their estimates for [ud] at \(d_{q-q} \approx 1.2\) fm. In order to compare diquark length scales to experiment, the diquark separation distance must be related to a N-N separation.

Experimental values of the relative momenta between two short-range correlated nucleons include 400 MeV/c for short-range neutron-proton correlations in \(^{12}\text{C}\) as well as a range of 300 – 600 MeV/c found in earlier studies [32]. The transition to inclusion of \(p-p\) short-range correlations occurs at \(\sim 800\) MeV/c [32]. These momenta correspond to a range of N-N separation distances from \(d_{N-N} = 0.25\) fm for \(\Delta p \sim 800\) MeV/c to \(d_{N-N} = 0.66\) fm for \(\Delta p \sim 300\) MeV/c by simple natural unit conversion where 1 fm corresponds to 200 MeV. These estimates suggest that valence quarks in correlated nucleons are well within the calculated quark-quark separation distance of the diquark.

All relative N-N momenta measured in short-range correlations as of today have been above the nuclear Fermi momentum. It is proposed that a sufficient N-N separation distance in order for diquark formation to occur is the distance corresponding to the Fermi momentum of the nucleus, \(k_F = 250\) MeV/c. This translates, by the same natural unit conversion, to a separation distance of 0.79 fm. Therefore, the phenomenologically driven separation distance between nearest neighbor nucleons sufficient for diquark formation induced SRC to occur is proposed to be

\[
d_{N-N} \lesssim d_F = 0.79\text{ fm.}
\]

V. ISOINP DEPENDENCE OF DIQUARK INDUCED SRC

The unexpected distortion of nucleon structure functions and the relevant strengths of \(n-p, n-n\) and \(p-p\) short-range correlations should have a theoretical foundation at the QCD level. Diquark formation across nucleons offers an underlying SU(3)_C explanation for isospin dependent SRC as well as predicting significant deviations from \(n-p\) dominance in \(A=3\) nuclei. The deviations depend upon the internal configuration of the valence quarks inside nucleons. There are two possibilities at lowest order (i.e. for 3-quark Fock states in the nucleon wavefunction), a 3-valence quark configuration, \([qq\bar{q}]\), and a quark-diquark configuration, \([q|ud]\).

In the quark-diquark approach to nucleon structure [41–44], formation of the energetically favored scalar [ud] diquark requires the nucleons to have available valence quarks with total isospin \(I = 0\). In this scenario, each nucleon already contains one [ud] diquark and therefore neutron-proton interactions dominate due to the available valence quark flavors,

\[
p - n: \quad |[ud u]| |[ud d]| \quad (16)
\]

\[
p - p: \quad |[ud u]| |[ud u]| \quad (17)
\]

\[
n - n: \quad |[ud d]| |[ud d]| \quad (18)
\]

in the N-N systems. Neutron-proton correlations were labeled “isophobic” short-range correlations and were first discovered at Brookhaven National Laboratory [45, 46]. They have subsequently been extensively studied by the CLAS collaboration at Jefferson Laboratory [29, 47, 48]. For two nucleons with a 3-valence quark internal configuration, any nuclear isospin combination of N-N pairs can form [ud] diquarks. In this case, neutron-proton correlations are favored by simple counting arguments; a factor of \(\frac{3}{2}\) in favor of \(n-p\) because there are a maximum of 5 possible [ud] diquarks in the \(n-p\) system as opposed to 4 in the \(n-n\) (or \(p-p\)) systems. Both cases predict a distortion of quark distributions inside nuclei but the strength of the “isophobic” nature of short-range correlations differs.
A. Predictions for A=3 nuclei

For A=3 nuclei with all nucleons in a quark-diquark internal configuration, only \( n - p \) SRC can form within the diquark induced SRC model. By inspection of the 9-quark flavor content of the tritium nucleus \( ^3\text{H} \),

\[
^3\text{H} : |p\rangle |n\rangle |n\rangle \propto |u[u|d]]|[u|d]|d]\rangle
\]

and the \(^3\text{He} \) nucleus,

\[
^3\text{He} : |p|p\rangle |n\rangle \propto |u|u|u]|d||u|d|d]\rangle,
\]

the case is made. The ratio of the number of \( n - n \) or \( p - p \) to \( n - p \) SRC in this case is zero. In contrast, 3-valence quark nucleon structure modifies the isospin dependence of N-N SRC less dramatically.

The number of possible diquark combinations in A=3 nuclei with nucleons in the 3-valence quark configuration is found by simple counting arguments. First, the 9 quarks of \(^3\text{He} \) with nucleon location indices are written as:

\[
N_1 : p \supset u_{11} u_{12} d_{13}
N_2 : p \supset u_{21} u_{22} d_{23}
N_3 : n \supset u_{31} d_{32} d_{33}
\]

where the first index of \( q_{ik} \) labels which of the 3 nucleons the quark belongs to, and the second index indicates which of the 3 valence quarks it is. Diquark induced SRC requires the first index of the quarks in the diquark to differ, \([u_{ij}d_{kl}]\) with \( i \neq k \). The 4 possible combinations from \( n - p \) SRC are listed below.

\[
\begin{align*}
u_{11}d_{23} & \quad u_{12}d_{23} \\ u_{21}d_{13} & \quad u_{22}d_{13}
\end{align*}
\]

Short-range correlations from \( n - p \) pairs have 10 possible combinations,

\[
\begin{align*}
u_{11}d_{32} & \quad u_{12}d_{32} \\ u_{11}d_{33} & \quad u_{12}d_{33} \\ u_{21}d_{23} & \quad u_{22}d_{23} \\ u_{21}d_{33} & \quad u_{22}d_{33} \\ u_{31}d_{13} & \quad u_{31}d_{23}
\end{align*}
\]

which gives the number of \( p - p \) combinations to \( n - p \) combinations in this case as \( \frac{2}{5} \).

Combining these results yields the following inequality for the isospin dependence of N-N SRC:

\[
^3\text{He} : 0 \leq \frac{N_{np}}{N_{nn}} \leq \frac{2}{5}
\]

where \( N_{NN} \) is the number of SRC between the nucleon flavors in the subscript.

The same argument may be made for \(^3\text{H} \) due to the quark-level isospin-0 interaction, to find

\[
^3\text{H} : 0 \leq \frac{N_{nn}}{N_{np}} \leq \frac{2}{5}.
\]

The fraction of same-nucleon N-N SRC is related to the coefficients of the lowest order Fock states for A=3 nuclei, as will be discussed in Sec. B. It is not possible to obtain ratios greater than \( \frac{2}{5} \) with diquark formation across nucleons. Finding such experimental values would rule the model out.

B. A=3 Nuclear wavefunction implications

Individual nucleon wavefunctions at lowest order are dominated by two Fock states with unknown coefficients; the 3 valence quark configuration and the quark-diquark configuration,

\[
|\Psi_{A=3}\rangle \propto (\alpha|qqq\rangle + \beta|q[qq]\rangle)
\]

where square brackets indicate the spin-0 \([ud]\) diquark. The full A=3 nuclear wavefunction is given by

\[
|\Psi_{A=3}\rangle \propto (\alpha|qqq\rangle + \beta|q[qq]\rangle)(\gamma|qqq\rangle + \delta|q[qq]\rangle)
\]

with mixed terms demonstrating that it is not straightforward to map the \( \frac{N_{np}}{N_{nn}} \) ratio to precise coefficients for each nucleon’s Fock states. A perhaps reasonable simplification is to assume that the proton and the neutron have the same coefficients for their 2-body and 3-body valence states, i.e. to set \( \gamma = \alpha \) and \( \delta = \beta \) in Eq. 28. In this case, the nuclear wavefunction reduces to

\[
|\Psi_{A=3}\rangle \propto \alpha^2|qqq\rangle^3 + \alpha^2\beta|qqq\rangle^2|q[qq]\rangle + 2\alpha\beta^2|qqq\rangle|q[qq]\rangle^2 + \beta^3|q[qq]\rangle^3
\]

With this assumption, the limiting cases yield exact knowledge of the coefficients: Experimental \(^3\text{H} \) values of \( \frac{N_{np}}{N_{nn}} = \frac{2}{5} \) implies \( \beta = 0 \), and \( \frac{N_{nn}}{N_{np}} = 0 \) implies \( \alpha = 0 \). Intermediate values for \( \frac{N_{nn}}{N_{np}} \) imply mixed internal configurations for the nucleons. The case is the same for the \( \frac{N_{np}}{N_{nn}} \) ratios of \(^3\text{He} \).

VI. DIQUARK FORMATION IN \(^2\text{H} \)

Diquark formation across the proton and neutron in \(^2\text{H} \) is different from other nuclei because the N-N system must remain a color singlet and the ground state deuteron is spin-1 due to spin-statistics restrictions on the \( n - p \) nuclear wavefunction. At the quark level, a 6-quark wavefunction does not allow a ground state \([ud]\) diquark to form across nucleons with an internal quark-diquark configuration due to Bose statistics constraints upon diquark exchange. This can be seen by considering both \( n \) and \( p \) in a quark-diquark structure and building a 3-diquark wavefunction with individual diquark wavefunctions given by Eq. 2. The combination of 3 such wavefunctions, each antisymmetric in color, spin and isospin while symmetric in space, has Fermi statistics upon diquark exchange and is therefore forbidden.
Diquark formation in this case cannot work even with a \((ud)\) vector diquark correlation between the \(n - p\) system. The triple diquark state in this case contains only two identical scalar diquarks but they pick up a minus sign upon exchange in the full wavefunction,

\[
|\Psi_{2H}\rangle \propto e^{abc}(ud)^a[ud]^b[ud]^c
\]  

(31)
due to color indices \(abc\), and diquark formation induced SRC are therefore forbidden in this scenario.

For nucleons in a 3-valence quark internal structure, both scalar and vector diquarks can form between the \(ud - udd\) quarks of the deuteron, but the overall configuration must respect the \(S = 1\) ground state. Thus for a single \([ud]\) to form the remaining quarks must combine into a spin-1 state, together with any gluon and orbital angular momentum contributions. In this scenario, a reduction in the EMC effect is predicted because the maximum total number of scalar diquarks (different from the number of possible combinations that can create \([ud]\)) that can form across the \(n - p\) system is 2 due to spin-statistics constraints on the system. This reduction is as compared to structure function distortions extrapolated from the EMC-SRC effect in higher nuclei (higher nuclei not divided through by the deuteron’s structure function) [49]. Experimental results from the BONuS experiment at Jefferson Lab do show structure function distortions in the deuteron [50], with a possible reduction in strength as defined above [51].

For \(A > 2\) nuclei, if diquarks behave as QCD Cooper pairs and allow for a breaking of SU(3)\(_C\) in the 2-nucleon system, 3 scalar diquarks may be able to form due to the non-isolated strongly bound environment created by additional nucleons. An important question as to the boundary condition of such a system remains. The possibility of diquark superconducting states is an active area of research, with particular relevance to studies of the cores of neutron stars [52–58].

### VII. CONCLUSIONS

Diquark formation across a pair of nucleons is proposed as the cause of the structure function distortions of the EMC effect at the quark and gluon level of QCD. The quark-quark QCD potential is attractive in the \(\bar{S}C\) channel of SU(3)\(_C\) and forms a bound state. The binding energy of the scalar isospin singlet \([ud]\) diquark is 148 ± 9 MeV making it a highly energetically favorable bond. Nucleon-nucleon separation distances sufficient for diquark formation are phenomenologically estimated from the Fermi momentum scale, found to be \(d_{N-N} \lesssim 0.79\) fm between neighboring nucleons.

The strength of the EMC effect in this model increases with increasing \(A\) as any two nucleons in close enough proximity to sense the attractive SU(3)\(_C\) quark-quark potential will form a color anti-triplet. The EMC effect strength increase with \(A\) has been measured [33].

Diquark formation is proposed as the underlying QCD physics of nucleon-nucleon short-range correlations. Scalar \([ud]\) diquark formation is proposed to be the dominant QCD-level physics responsible for the short-range N-N correlation model explanation of the EMC effect in all nuclei.

Isospin dependent N-N short-range correlation studies by the E12-11-112 experiment at Jefferson Lab are expected in the near future. The experiment is predicted to observe the number of \(n - n\) (or \(p - p\)) SRC to \(n - p\) SRC in \(A = 3\) to fall within the range \(0 \lesssim \frac{N_{nn}}{N_{np}} \lesssim \frac{2}{3}\) if the diquark formation model is correct. The upper limit of \(\frac{2}{3}\) is a hard cutoff for the diquark formation model; higher values rule the model out. The precise value of the ratio of neutron-proton to neutron-neutron or proton-proton SRC will be the first quantitative indication of the internal configuration of the valence quarks in \(A = 3\) nucleons.

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