Diquarks & Hidden Color Singlets: Particle Physics Signatures in Nuclear Physics

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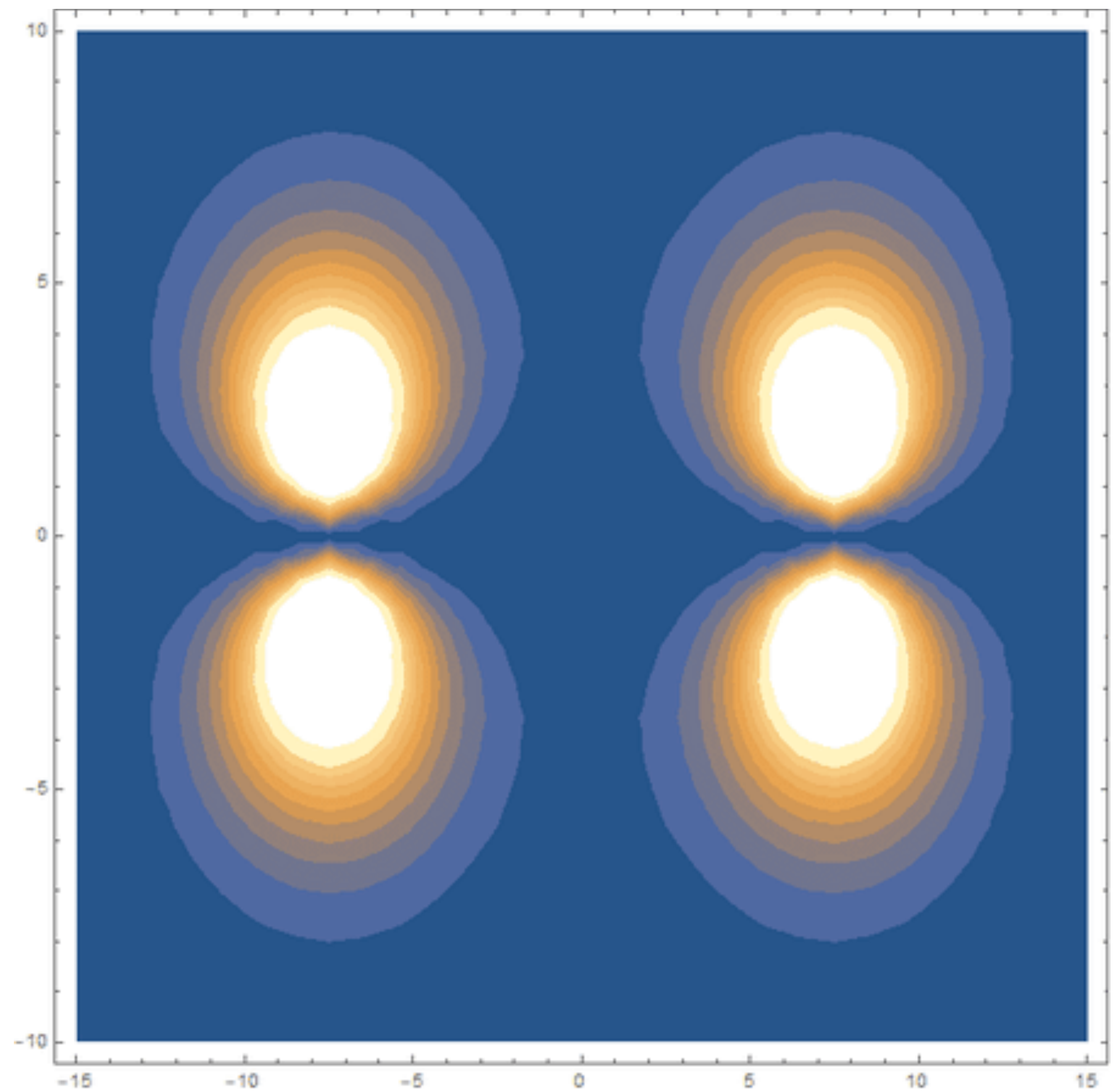
Talk outline

Based on previous and ongoing work with Stan Brodsky & parallel solo work

- Diquarks defined
- Hidden-color states defined
- Where do these objects show up? EMC effect, ATOMKI, JLab, EIC, …
- Hexadiquark implications: $^{4}\mathrm{He}$, tetraneutron, tetraproton



Diquarks

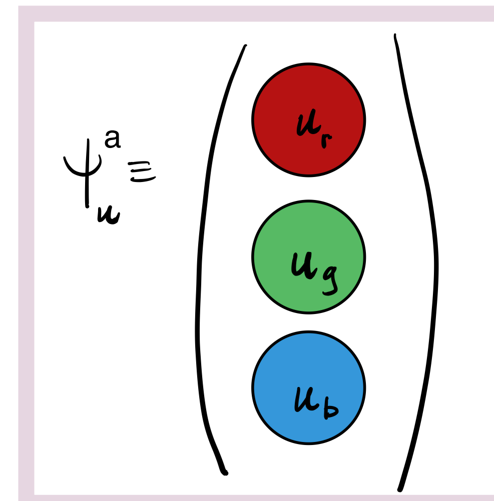
- Group theory rules of SU(3) $\Longrightarrow$ 2 quarks combine into anti-color charged object: $3_C \times 3_C \rightarrow \bar{3}_C$

If this combination does not occur - something must forbid it

- $\exists$ a short-range QCD Coulomb potential between quarks:

$$V(r_{qq}) \propto 1/r$$

Quark in the fundamental rep of $SU(3)_C$:



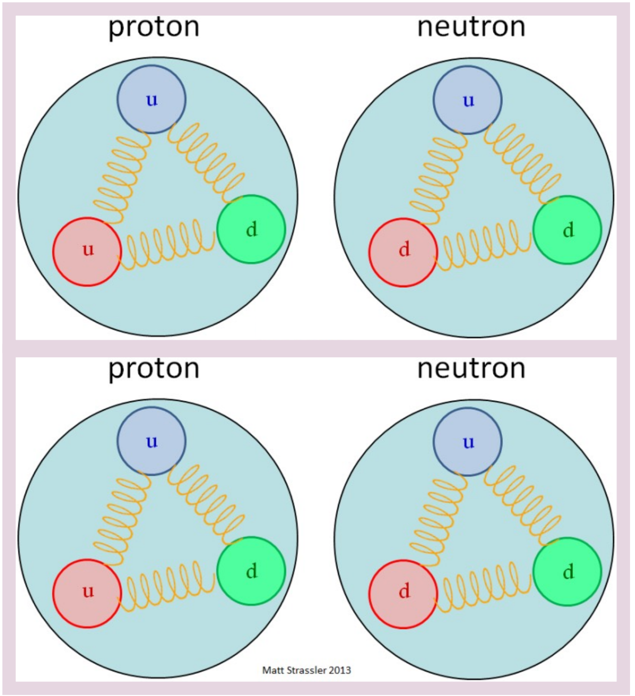
Diquark wavefunction in the antifundamental rep of $SU(3)_C$:

$$\psi_a^{[ud]} = \frac{1}{\sqrt{2}} \epsilon_{abc} \left(u^b_\uparrow d^c_\downarrow - d^b_\uparrow u^c_\downarrow \right)$$

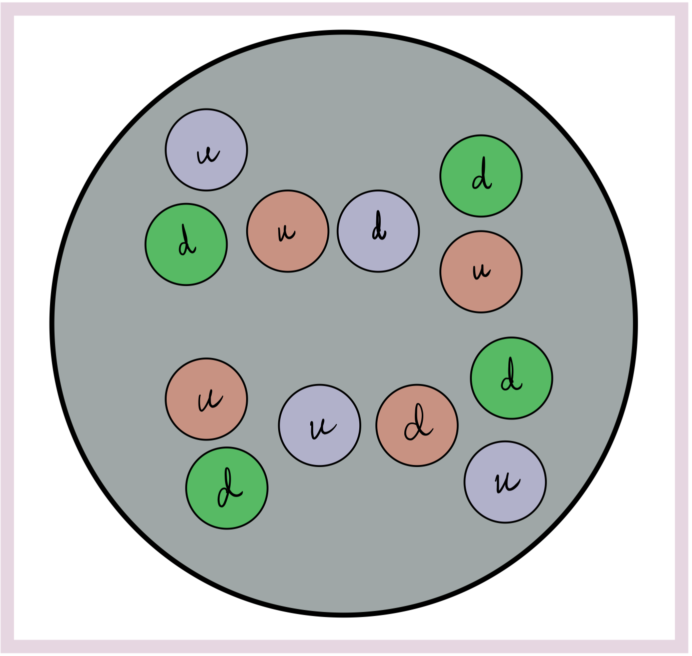
Hidden-color *singlet* states: components of nuclear wavefunctions

- Nuclei contain multiple nucleons, i.e., multiple color singlets
- Hidden-color states are SINGLE color singlets created out of the same # of quarks
- Ex: Deuterium hidden-color states are 6 quark color singlets with the quantum numbers of ^2H
- Group theory rules of SU(3) again! Do not create a 1_C until the last step of wf build

^{4}He nucleus containing 4 color singlets



^{4}He nucleus containing 1 color singlet



Hexadiquark wavefunction:

The HdQ is a $\mathrm{J^P = 0^+, \;\; I = 0}$ hidden-color component of the $^4\mathrm{He}$ nuclear wavefunction:

$$|\alpha\rangle = C_{pnpn}\left|(u[ud])_{1_C}(d[ud])_{1_C}(u[ud])_{1_C}(d[ud])_{1_C}\right\rangle + C_{\mathrm{HdQ}}\left|([ud][ud])_{\overline{6}_C}([ud][ud])_{\overline{6}_C}([ud][ud])_{\overline{6}_C}\right\rangle$$

All quantum numbers of the HdQ and the $^4\mathrm{He}$ ground state are identical: Q=2, B=4, I=0, J=0

Important: HdQ requires 2 neutron-proton pairs. The effect of the HdQ is "isophobic" because $[ud]$ diquarks form only across n-p pairs in the quark-diquark nucleon configuration. EMC effect must be n-p dominated.

To construct the HdQ wave function we follow the three-step procedure described above. The scalar diquark $\psi_a^{[ud]}$ is given by the spin-isospin singlet product

$$\begin{aligned}\psi_a^{[ud]} &= [ud]_a \\ &= \frac{1}{\sqrt{2}}\epsilon_{abc}(u^b\uparrow d^c\downarrow - d^b\uparrow u^c\downarrow),\end{aligned} \tag{6}$$

where the indices $a, b, c = 1, 2, 3$ are color indices in the fundamental $SU(3)_C$ representation. The scalar diquark is a $\mathrm{J^P} = 0^+, \mathrm{I} = 0$ object which transforms as color $\overline{\mathbf{3}}$.

In the second step we construct the DdQ, $\psi^{[udud]}$, the product $\overline{\mathbf{3}}_C \otimes \overline{\mathbf{3}}_C$ from two scalar diquarks. It is the sum of a $\mathbf{3}_C$ and a $\overline{\mathbf{6}}_C$ represented by the symmetric tensor (A.3). The DdQ, $\psi^{[udud]}$, is thus given by the symmetric tensor operator

$$\psi_{ab}^{[udud]} = \psi_a^{[ud]}\psi_b^{[ud]}, \tag{7}$$

an isospin singlet state which transforms in the symmetric $\overline{\mathbf{6}}$ color representation under $SU(3)_C$ transformations. The DdQ itself is also an effective scalar boson since it is the product of two scalar bosons: It transforms as a $\mathrm{J^P} = 0^+$ state under SO(3) rotations.

Lastly, we construct the HdQ which is the color singlet product of three DdQ in the $\overline{\mathbf{6}}_C$. To this end, we first construct the symmetric $\mathbf{6}_C$ out of the product of two $\overline{\mathbf{6}}_C$ in the complex conjugate representation: $\overline{\mathbf{6}}_C \otimes \overline{\mathbf{6}}_C \to \mathbf{6}_C$. It is given by the symmetric tensor (A.11). The HdQ wave function, ψ_{HdQ}, is thus the color singlet

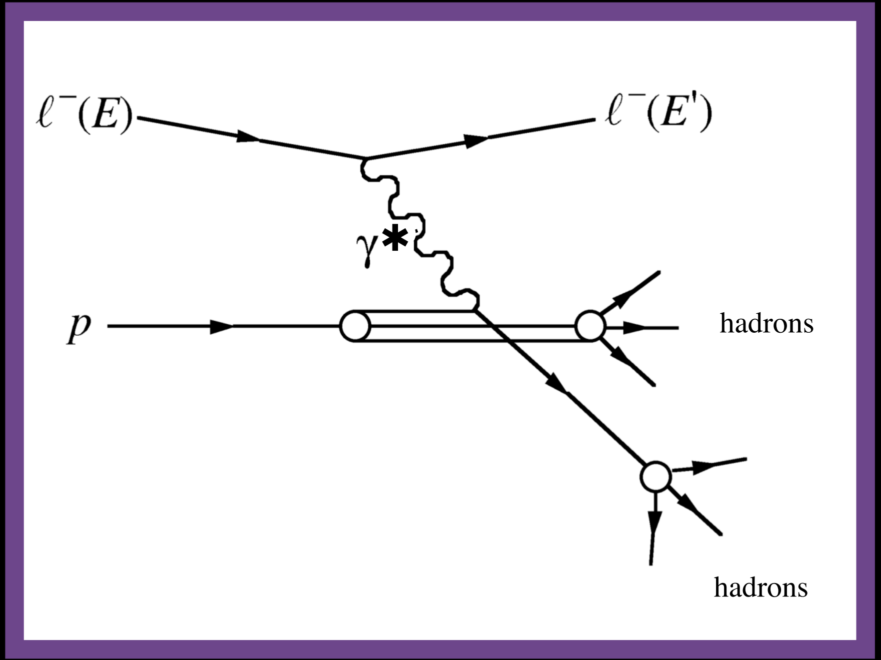
$$\psi_{HdQ} = \epsilon^{acf}\epsilon^{bdg}\psi_{ab}^{[udud]}\psi_{cd}^{[udud]}\psi_{fg}^{[udud]}, \tag{8}$$

which, as required, is fully symmetric with respect to the interchange of any two bosonic duo-diquarks. The HdQ spatial wave function must also be totally symmetric with respect to the exchange of any two DdQs in order for the total wavefunction to obey the correct statistics. The HdQ is a $\mathrm{J^P} = 0^+$, I=0 color singlet state, matching the quantum numbers of the ^{4}He nucleus ground state.

"QCD hidden-color hexadiquark in the core of nuclei," JRW, Brodsky, de Teramond, Goldhaber, Schmidt, *Nucl.Phys.A* 1007 (2021), arXiv:2004.14659

Gateway from QCD to nuclear: EMC effect

- Deep inelastic scattering (DIS) experiments
- Lepton scatters from target, exchanging virtual photon with 4-momentum q^2 given by: $Q^2 \equiv -q^2 = 2EE'(1-\cos\theta)$
- γ^* strikes quark: The fraction of nucleon momentum carried by the struck quark is known via the Bjorken scaling variable $x_B = \dfrac{Q^2}{2M_p\nu}$ where $\nu = E - E'$, M_p=mass of proton, lepton mass neglected



Adapted from Nuclear & Particle Physics by B.R. Martin, 2003

Differential cross section for DIS:

$$\frac{d\sigma}{dxdy}\left(e^-p \to e^-X\right) = \sum_f x\, e_f^2 \left[\, q_f(x) + \bar{q}_{\bar{f}}(x)\right] \cdot \frac{2\pi\alpha^2 s}{Q^4}\left(1+(1-y)^2\right)$$

where $y = \dfrac{\nu}{E}$ is the fraction of ℓ^- energy transferred to the target. $F_2(x)$ is the **nucleon structure function**, defined as:

$$F_2(x_B) \equiv \sum_f x_B\, e_f^2 \left(\, q_f(x_B) + \bar{q}_{\bar{f}}(x_B)\right)$$

in terms of quark distribution functions $q_f(x)$: probability to find a quark with momentum $x_i \in [x, x+dx]$.

EMC effect: Distortion of nuclear structure functions

$$\text{Plotting ratio of } F_2(x_B) \equiv \sum_f x_B\, e_f^2 \left(q_f(x_B) + \bar{q}_{\bar{f}}(x_B) \right) \text{ vs. } x_B$$

- Predicted $F_2(x_B)$ ratio in complete disagreement with theory
- Why should quark behavior - confined in nucleons at QCD energy scales ~200 MeV - be so affected when nucleons embedded in nuclei, BE $\geq$ 2.2 MeV?
- Mystery has not been solved to this day.

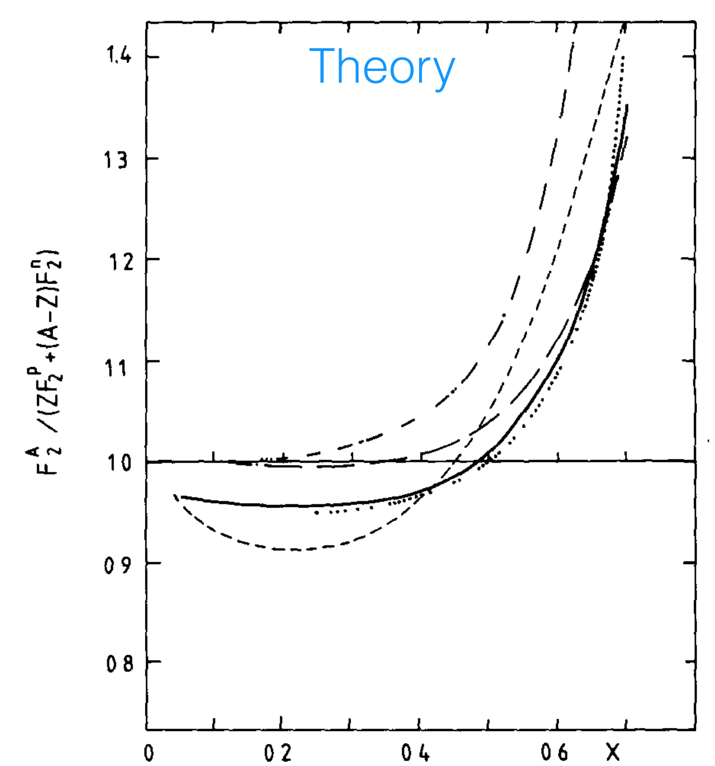


Fig. 1. Theoretical predictions for the Fermi motion correction of the nucleon structure function F_2^N for iron. Dotted line Few-nucleon-correlation-model of Frankfurt and Strikman [9]. Dashed line. Collective-tube-model of Berlad et al. [10] Solid line Correction according to Bodek and Ritchie [8]. Dot–dashed line. Same authors, but no high momentum tail included. Triple-dot–dashed line Same authors, momentum balance always by a $A-1$ nucleus. The last two curves should not be understood as predictions but as an indication of the sensitivity of the calculations to several assumptions which are only poorly known.

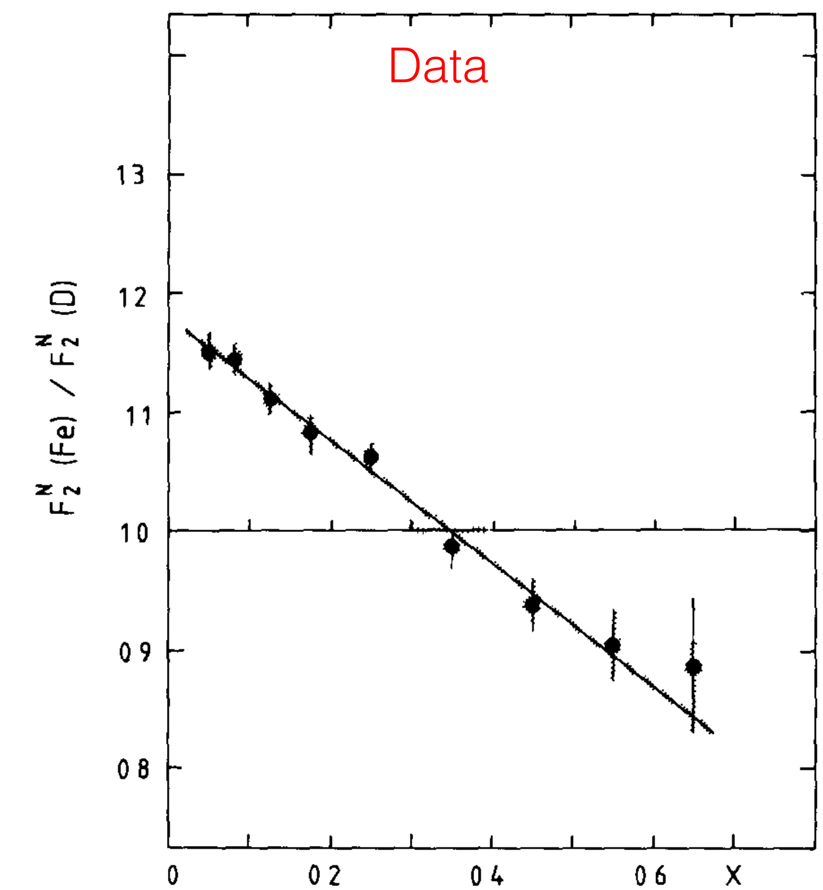


Fig. 2. The ratio of the nucleon structure functions F_2^N measured on iron and deuterium as a function of $x = Q^2/2M_p\nu$. The iron data are corrected for the non-isoscalarity of $^{56}_{26}$Fe, both data sets are not corrected for Fermi motion. The full curve is a linear fit $F_2^N(\text{Fe})/F_2^N(\text{D}) = a + bx$ which results in a slope $b = -0\ 52 \pm 0.04$ (stat.) $\pm$ 0.21 (syst) The shaded area indicates the effect of systematic errors on this slope.

"THE RATIO OF THE NUCLEON STRUCTURE FUNCTIONS F_2^N FOR IRON AND DEUTERIUM "
The European Muon Collaboration, J.J. AUBERT et al. 1983

EMC effect experiments & explanations

Possible explanations

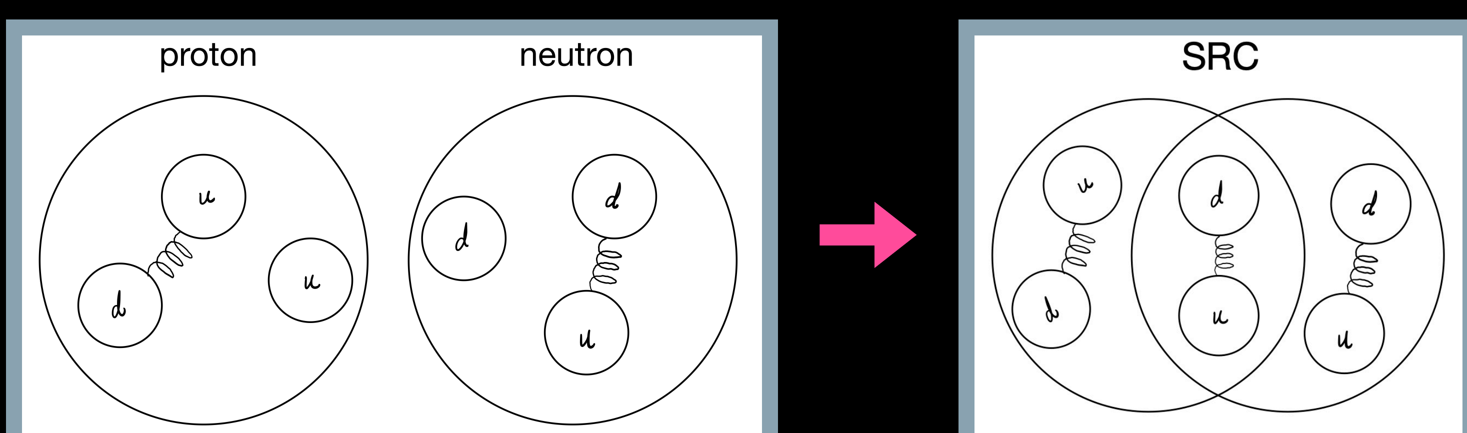
- Mean field effects involving the whole nucleus
- Local effects, *e.g.*, 2-nucleon correlations

Simple mean field effects inconsistent with the EMC effect in light nuclei - MC of ^{9}Be $\Longrightarrow$clustering
Seely *et al.*, 2009.

"This one new bit of information has reinvigorated the experimental and theoretical efforts to pin down the underlying cause of the EMC effect." *Malace et al., 2014*

Short-range N-N correlated pairs (SRC) may cause EMC effect (first suggested in *Ciofi & Liuti 1990, 1991*).
Neutron-proton pairs later found to dominate SRC (CLAS collaboration & others)

New model: **Diquark formation** proposed to create short-range correlations (SRC), modifying quark behavior in the NN pair



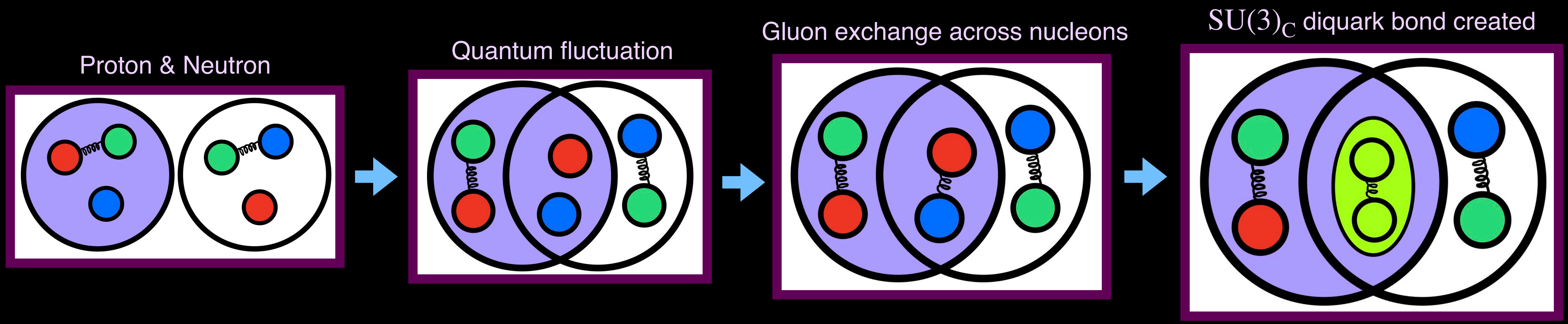
Dozens of experiments confirm EMC effect

Target	Collaboration/ Laboratory
^{3}He	JLab HERMES
^{4}He	JLab SLAC NMC
^{6}Li	NMC
^{9}Be	JLab SLAC NMC
^{12}C	JLab SLAC NMC EMC
^{14}N	HERMES BCDMS
^{27}Al	Rochester-SLAC-MIT SLAC NMC
^{40}Ca	SLAC NMC EMC
^{56}Fe	Rochester-SLAC-MIT SLAC NMC BCDMS
^{64}Cu	EMC
^{108}Ag	SLAC
^{119}Sn	NMC EMC
^{197}Au	SLAC
^{207}Pb	NMC

Malace, Gaskell, Higinbotham & Cloet, Int.J.Mod.Phys.E 23 (2014)

Overview: Fundamental QCD dynamics in NN pairs

New model: **Diquark formation** proposed to create short-range correlations (SRC), modifying quark behavior in the NN pair



Short-range QCD potentials act on distance scales < 1 fm. Strong NN overlap can bring valence quarks within range.

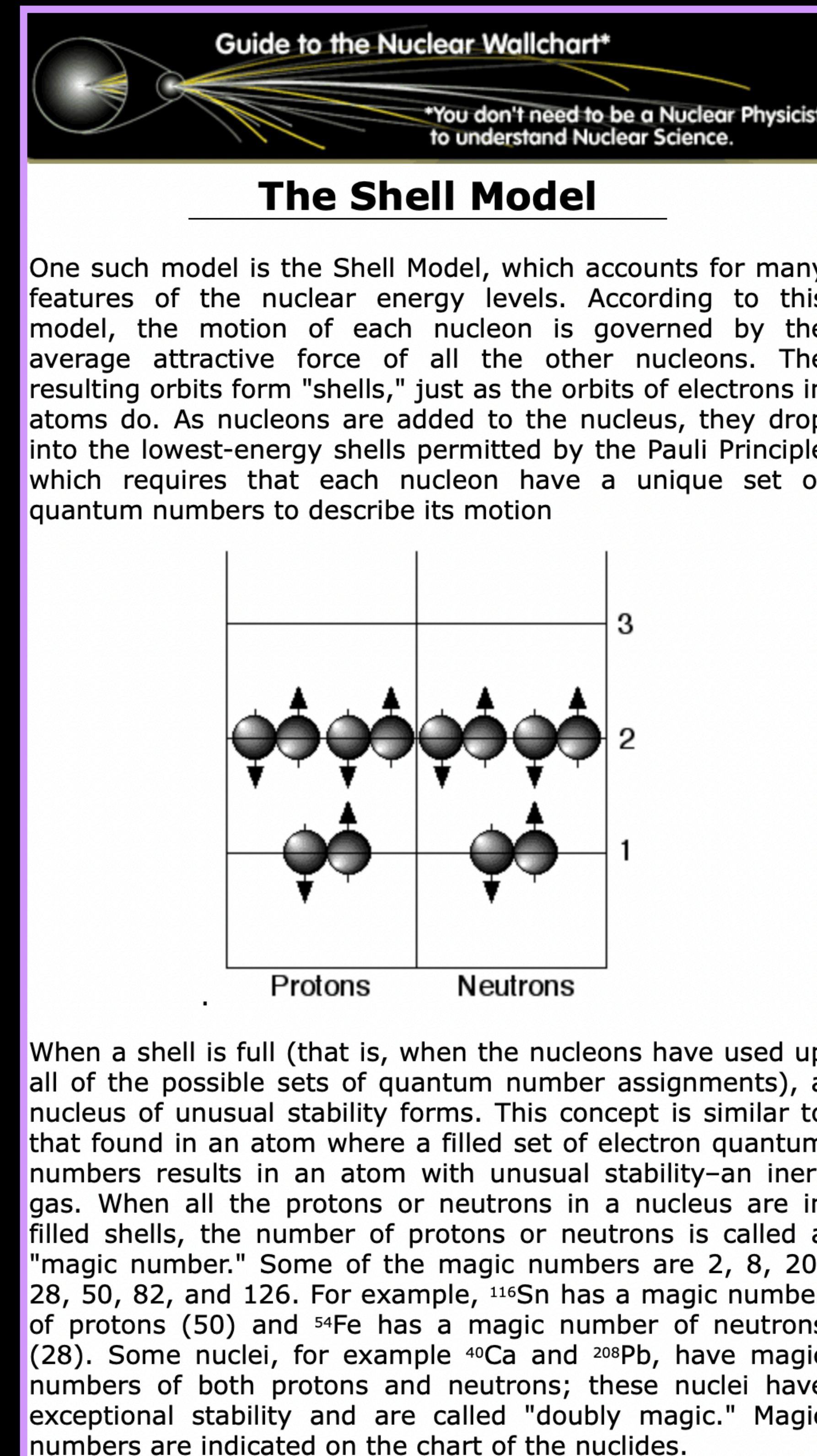
What are SRC?

Short-range correlated nucleon-nucleon pairs

- Nuclei consist of protons and neutrons ~80% of which are organized into shells/ LRC
- Nuclear shell model is a "description of nuclei of atoms by analogy with the Bohr atomic model of electron energy levels.
- It was developed independently in the late 1940s by the American physicist Maria Goeppert Mayer and the German physicist J. Hans D. Jensen, who shared the Nobel Prize for Physics in 1963 for their work."
  - *William L. Hosch, www.britannica.com*

~20% of nucleons are in short-range correlated pairs - not shells/LRC

- SRC have very high relative momentum - nearly all nucleons above the Fermi momentum of the nucleus, $k_F \sim 250\ \mathrm{MeV/c}$, are in SRC



Guide to the Nuclear Wallchart*

*You don't need to be a Nuclear Physicist to understand Nuclear Science.

The Shell Model

One such model is the Shell Model, which accounts for many features of the nuclear energy levels. According to this model, the motion of each nucleon is governed by the average attractive force of all the other nucleons. The resulting orbits form "shells," just as the orbits of electrons in atoms do. As nucleons are added to the nucleus, they drop into the lowest-energy shells permitted by the Pauli Principle which requires that each nucleon have a unique set of quantum numbers to describe its motion

When a shell is full (that is, when the nucleons have used up all of the possible sets of quantum number assignments), a nucleus of unusual stability forms. This concept is similar to that found in an atom where a filled set of electron quantum numbers results in an atom with unusual stability–an inert gas. When all the protons or neutrons in a nucleus are in filled shells, the number of protons or neutrons is called a "magic number." Some of the magic numbers are 2, 8, 20, 28, 50, 82, and 126. For example, ^{116}Sn has a magic number of protons (50) and ^{54}Fe has a magic number of neutrons (28). Some nuclei, for example ^{40}Ca and ^{208}Pb, have magic numbers of both protons and neutrons; these nuclei have exceptional stability and are called "doubly magic." Magic numbers are indicated on the chart of the nuclides.

www2.lbl.gov/abc/wallchart/chapters/06/1.html

What are diquark-induced short-range correlations (SRC)?

Diquark-induced SRC

What causes the "short-range" part of short-range NN correlations?

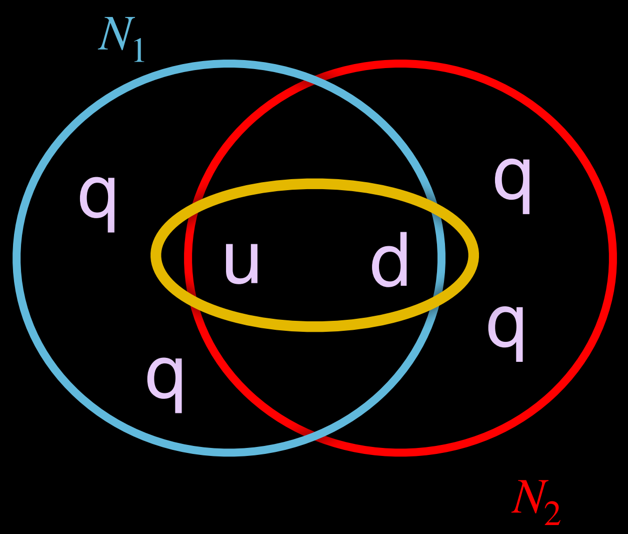
- Quantum fluctuations in separation distance between 2 nucleons

and/or

- Quantum fluctuations in relative momentum between 2 nucleons

What causes the "correlation" in SRC?

- Diquark forms across nucleons
- Valence quarks from different nucleons "fall into" short-range QCD potential V(r)
- Highly energetically favorable $[ud]$ diquark created, a spin-0, isospin-0 qq combination

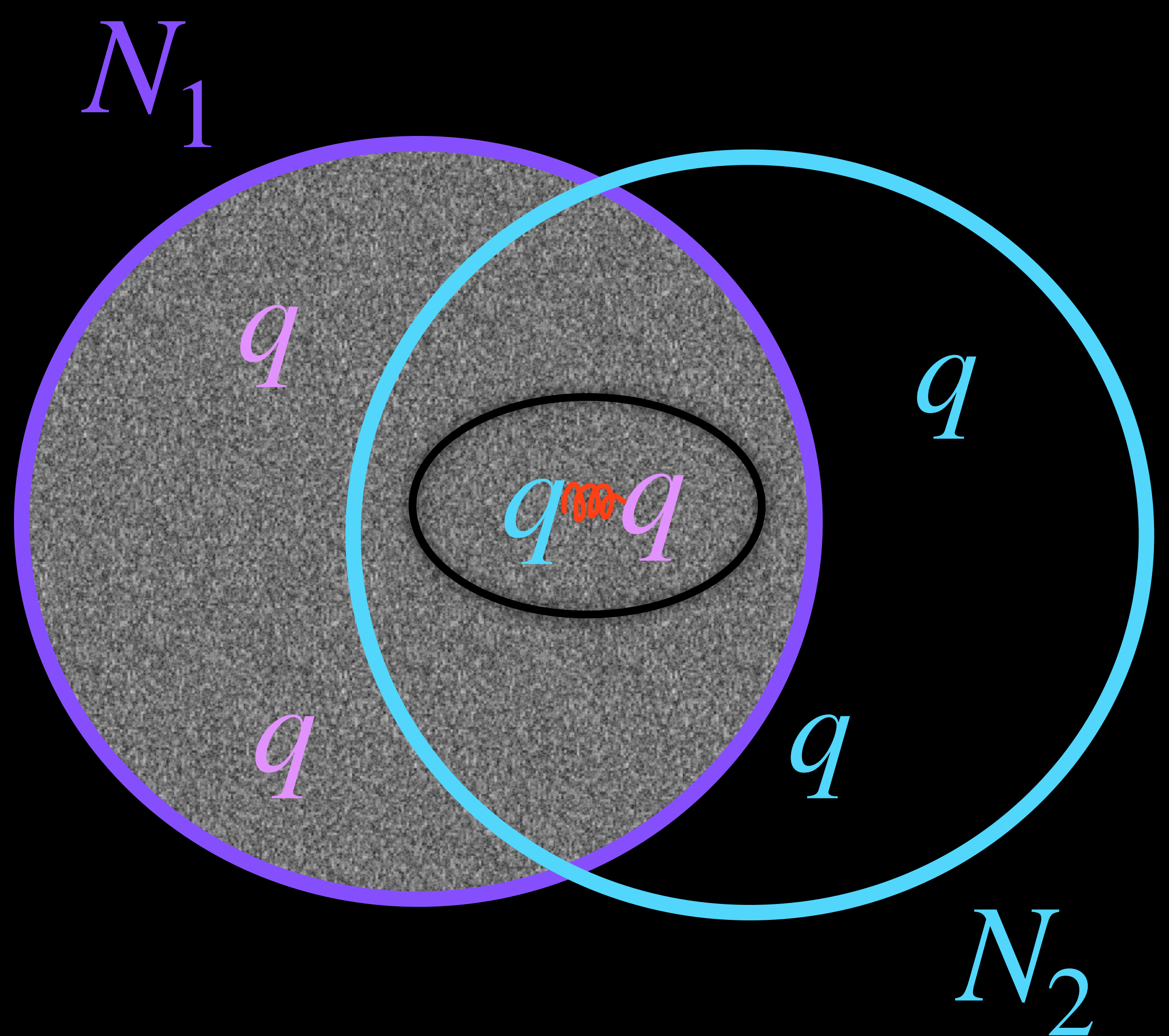


What are the requirements for a diquark to form in the nuclear environment?
(not inside of a single baryon)

Diquark formation across N-N pairs

Requirements for diquark induced SRC:

1. Nucleon-Nucleon wavefunctions must STRONGLY overlap
2. Attractive short-range QCD potential between valence quarks
3. Significant binding energy for diquark to form (much stronger than nuclear binding energies - comparable to confinement scale)



1. SRC 3D-overlap for relative momenta 400 MeV/c & 800 MeV/c

- *Plot 1*: According to the ^{12}C measurements from 2021 CLAS, NN tensor force dominates at 400 MeV/c relative momenta. Natural unit conversion gives 0.49 fm = 400 MeV/c.

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In[∘]:= Show[Graphics3D[{Opacity[0.3], Sphere[{{0, 0, 0}, {0.49, 0, 0}}, 0.84]}, Axes → True],
  Boxed → True, Background → Grey]
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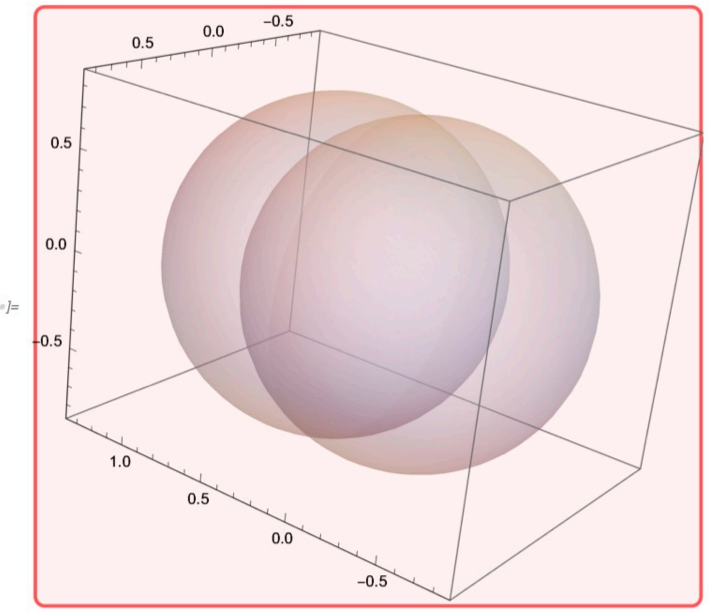

57% of nucleon volume is in the overlap region!

- *Plot 2*: Tensor-scalar transition momenta - according to the ^{12}C measurements from 2021 CLAS, NN scalar force is in effect at 800 MeV/c relative momenta . Natural unit conversion gives 0.25 fm = 800 MeV/c .

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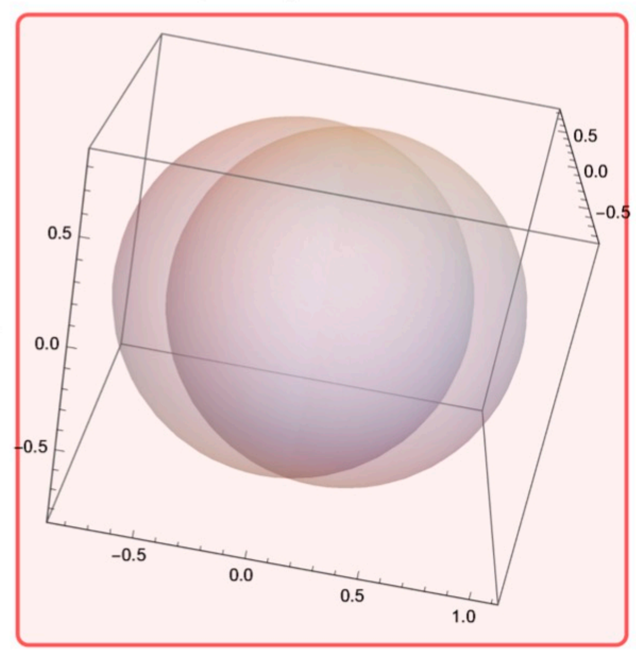


78% of nucleon volume is in the overlap region!

2. Quark-quark potential in QCD: $V(r)$ calculation

- The $\mathrm{SU}(3)_C$ invariant QCD Lagragian:

$$\mathscr{L}_{\mathrm{QCD}} = -\frac{1}{4}F^{\mu\nu a}F^{a}_{\mu\nu} + \bar{\Psi}_f\left(i\gamma^\mu D_\mu - m\right)\Psi_f$$

where covariant derivative $D_\mu = \partial_\mu - ig_s A^a_\mu t^a$ acts on quark fields, t^a are the 3x3 traceless Hermitian matrices (e.g. the 8 Gell-Mann matrices), g_s the strong interaction coupling, $\alpha_s \equiv \frac{g_s^2}{4\pi}$.

- QCD potential for states in representations R and R' is given by:

$$V(r) = \frac{g_s^2}{4\pi r} t^a_R \otimes t^a_{R'}$$

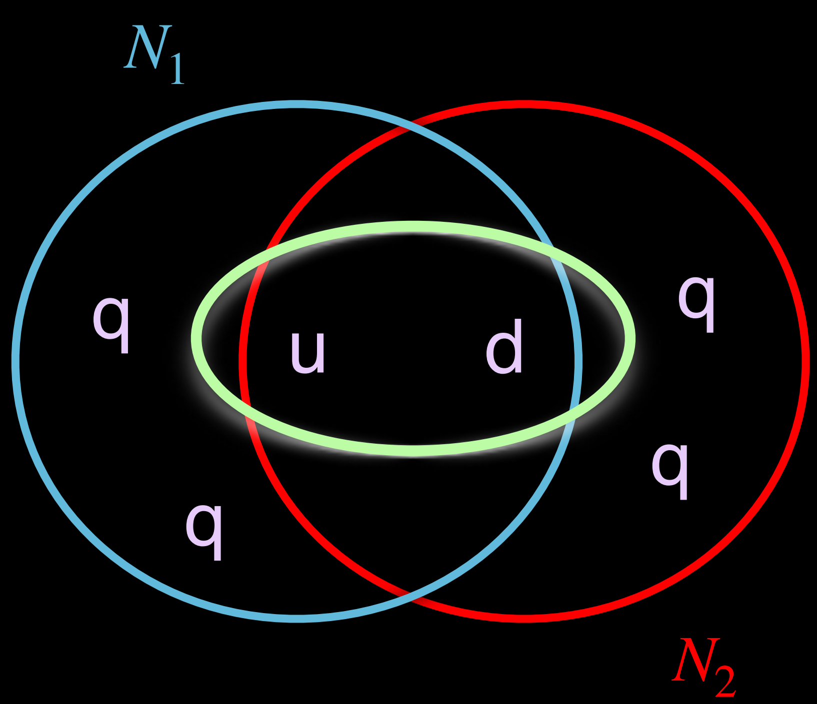
- To compute $V(r)$ for a $3_c \otimes 3_c \to \overline{3}_c$, we use the definition of the scalar $C_2(R)$, $t^a_R\, t^a_R \equiv C_2(R)\ \mathbf{1}$, the *quadratic Casimir operator* (NB: R_f is the final state representation):

$$V(r) = \frac{g_s^2}{4\pi r}\cdot\frac{1}{2}\cdot\left(C_2\left(R_f\right) - C_2(R) - C_2(R')\right)$$

- Diquarks combine 2 fundamental representation quarks into an anti-fundamental, $3_C \otimes 3_c \to \overline{3}_C$:

$$V(r) = -\frac{2}{3}\frac{g_s^2}{4\pi r} \Longrightarrow \text{Diquark is bound!}$$

Diquark induced N-N correlation:



Compare to color singlet attractive potential:

$$q\bar{q}:\quad V(r) = -\frac{4}{3}\frac{g_s^2}{4\pi r}$$

3. Diquark binding energy: Color hyperfine structure

Use Λ^0 baryon to find binding energy of $[ud]$:

$$\text{B.E.}_{[ud]} = m_u^b + m_d^b + m_s^b - M_{\Lambda^0}$$

Spin-spin interaction contribute to hadron mass;
QCD hyperfine interactions:

1. $$M_{(\text{baryon})} = \sum_{i=1}^{3} m_i + a' \sum_{i<j} \left(\sigma_i \cdot \sigma_j\right)/m_i m_j$$

2. $$M_{(\text{meson})} = m_1 + m_2 + a\left(\sigma_1 \cdot \sigma_2\right)/m_1 m_2$$

(de Rujula, Georgi & Glashow 1975, Gasiorowicz & Rosner 1981, Karliner & Rosner 2014)

Effective masses of light quarks are found using Eq.1 and fitting to measured baryon masses:

$$m_u^b = m_d^b \equiv m_q^b = 363 \text{ MeV}, \quad \text{m}_\text{s}^\text{b} = 538 \text{ MeV}$$

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

Relevant diquark-carrying baryons: Λ, Σ^+, Σ^0, Σ^-

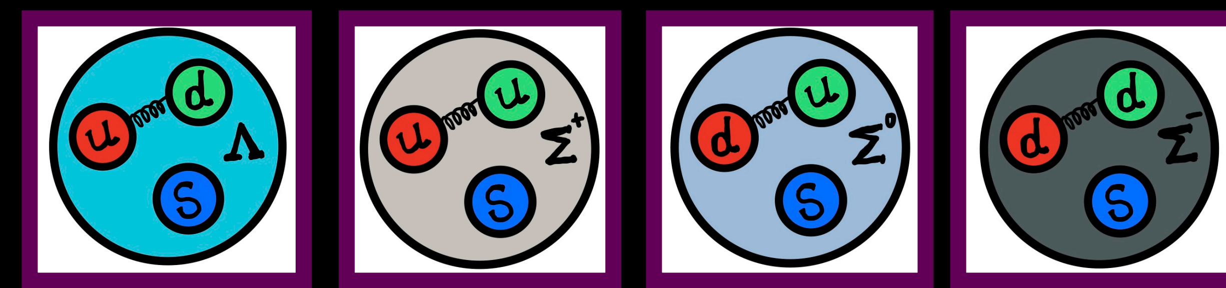


TABLE I: Diquark properties

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

Uncertainties calculated using average light quark mass errors $\Delta m_q = 5\ MeV$ *[37]*

TABLE II: Relevant $SU(3)_C$ hyperfine structure baryons [28]

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

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

"Diquark Induced Nucleon-Nucleon Correlations and the EMC Effect," JRW, arXiv:2009.06968

Diquark formation across N-N pairs

Requirements for diquark induced SRC:

1. Nucleon-Nucleon wavefunctions must STRONGLY overlap
2. Attractive short-range QCD potential between valence quarks
3. Significant binding energy for diquark to form (much stronger than nuclear binding energies - comparable to confinement scale)

What are the implications of NN diquark formation?
Quark flavor dependence of low mass $[ud]$ will affect the np vs. pp SRC!

Diquark formation prediction for A=3 SRC: Isospin

Nucleon wavefunction : $|\mathrm{N}\rangle = \alpha|\mathrm{qqq}\rangle + \beta|\mathrm{q[qq]}\rangle$

Scalar [ud] diquark formation for nucleons with 3-valence quark internal structure $|\mathrm{N}\rangle \propto |\mathrm{qqq}\rangle$:

$$^3H: \quad 2n + p \to 4u,\, 5d \implies np \supset [ud] \text{ x10} \qquad \implies nn \supset [ud] \text{ x4} \implies 60\,\%\, n-p,\ 40\,\%\, n-n$$

$$^3He: \quad 2p + n \to 5u,\, 4d \implies np \supset [ud] \text{ x10} \qquad \implies pp \supset [ud] \text{ x4} \implies 60\,\%\, n-p,\ 40\,\%\, p-p$$

Scalar diquark formation for nucleons in quark-diquark internal configuration $|\mathrm{N}\rangle \propto |\mathrm{q[qq]}\rangle$:

$$^3H: \quad u\,[ud] + u\,[ud] + d\,[ud] \implies 100\,\%\, n-p$$

$$^3He: \quad d\,[ud] + d\,[ud] + u\,[ud] \implies 100\,\%\, n-p$$

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}He with nucleon location indices are written as:

$$\begin{aligned} &\mathrm{N}_1: p \supset u_{11}\ u_{12}\ d_{13} \\ &\mathrm{N}_2: p \supset u_{21}\ u_{22}\ d_{23} \\ &\mathrm{N}_3: n \supset u_{31}\ d_{32}\ d_{33} \end{aligned} \tag{21}$$

where the first index of q_{ij} 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 $p-p$ SRC are listed below.

$$u_{11}d_{23} \quad u_{12}d_{23} \tag{22}$$

$$u_{21}d_{13} \quad u_{22}d_{13} \tag{23}$$

Short-range correlations from $n-p$ pairs have 10 possible combinations,

$$\begin{aligned} &u_{11}d_{32} \quad u_{12}d_{32} \\ &u_{11}d_{33} \quad u_{12}d_{33} \\ &u_{21}d_{32} \quad u_{22}d_{32} \\ &u_{21}d_{33} \quad u_{22}d_{33} \\ &u_{31}d_{13} \quad u_{31}d_{23} \end{aligned} \tag{24}$$

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:

$$^3\mathrm{He}: \quad 0 \leq \frac{\mathcal{N}_{pp}}{\mathcal{N}_{np}} \leq \frac{2}{5} \tag{25}$$

where $\mathcal{N}_{NN}$ is the number of SRC between the nucleon flavors in the subscript.

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

$$^3\mathrm{H}: \quad 0 \leq \frac{\mathcal{N}_{nn}}{\mathcal{N}_{np}} \leq \frac{2}{5}. \tag{26}$$

JRW, arXiv:2009.06968

Combine into isospin dependent SRC ratio predictions :

$$^3He: \quad 0 \leq \frac{N_{pp\ \mathrm{SRC}}}{N_{np\ \mathrm{SRC}}} \leq \frac{2}{5}, \quad ^3H: \quad 0 \leq \frac{N_{nn\ \mathrm{SRC}}}{N_{np\ \mathrm{SRC}}} \leq \frac{2}{5}, \quad Maximum\ 40\%!$$

Diquark formation induced SRC inequality tentatively confirmed: JLab experiment E12-11-112 A=3 mirror nuclei results

New Nature paper from JLab/LBNL: $\dfrac{\mathcal{N}_{\mathrm{pp}}}{\mathcal{N}_{\mathrm{np}}} = \dfrac{1}{4.23} \sim 0.24$

By Shujie Li, John Arrington & collaborators - just out!!

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,

$$|\mathrm{N}\rangle = \alpha|\mathrm{qqq}\rangle + \beta|\mathrm{q[qq]}\rangle, \tag{27}$$

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

$$|\Psi_{\mathrm{A}=3}\rangle \propto (\alpha|qqq\rangle + \beta|q[qq]\rangle)(\alpha|qqq\rangle + \beta|q[qq]\rangle) (\gamma|qqq\rangle + \delta|q[qq]\rangle) \tag{28}$$

where the proton and the neutron are allowed to have different weights for each valence quark configuration. This expands out to

$$|\Psi_{\mathrm{A}=3}\rangle \propto \alpha^2\gamma|qqq\rangle^3 + 2\alpha\beta\gamma|qqq\rangle^2|q[qq]\rangle \; \alpha^2\delta|qqq\rangle^2|q[qq]\rangle + \beta^2\gamma|qqq\rangle|q[qq]\rangle^2 + 2\alpha\beta\delta|qqq\rangle|q[qq]\rangle^2 + \beta^2\delta|q[qq]\rangle^3, \tag{29}$$

with mixed terms demonstrating that it is not straightforward to map the $\frac{\mathcal{N}_{pp}}{\mathcal{N}_{np}}$ 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

$$|\Psi_{\mathrm{A}=3}\rangle \propto \alpha^3|qqq\rangle^3 + 3\alpha^2\beta|qqq\rangle^2|q[qq]\rangle + 3\beta^2\alpha|qqq\rangle|q[qq]\rangle^2 + \beta^3|q[qq]\rangle^3. \tag{30}$$

JRW, arXiv:2009.06968

Isospin dependent SRC ratio inequalities from diquark induced SRC :

$$^3He: \quad 0 \le \frac{N_{pp\ \mathrm{SRC}}}{N_{np\ \mathrm{SRC}}} \le 0.4$$

$$^3H: \quad 0 \le \frac{N_{nn\ \mathrm{SRC}}}{N_{np\ \mathrm{SRC}}} \le 0.4$$

$\Longrightarrow$ Nucleon wavefunction MAY contain both $|\mathrm{qqq}\rangle$ and $|\mathrm{q[ud]}\rangle$ with approximately equal coefficients

$\Longrightarrow$ Diquark formation – single gluon exchange & $SU(3)_C$ transformation – favored over quark and diquark exchange.

Nuclear structure functions $F_2(x_B)$ from the diquark model?

Non-relativistic analysis: Diquark formation modification of F_2 from Fermi motion of quarks in SRC

Recall quark momentum distribution functions $\mathrm{q}(\mathrm{x_B})$: $F_2(x_B) \equiv \sum_f x_B\, e_f^2 \left(q_f(x_B) + \bar{q}_{\bar{f}}(x_B) \right)$

$$\text{Fermi energy :} \quad \mathrm{E_F} = \frac{\mathrm{p_F^2}}{2\mathrm{m}}$$

$$\text{Fermi momentum :} \quad \mathrm{p_F} = \sqrt{2\mathrm{m}\mathrm{E_F}} \propto \mathrm{m}^{\frac{1}{2}}$$

- Diquarks lower the mass of the system
- Effective masses of quarks in nucleons: $m_u = m_d = 363\ \mathrm{MeV}$
- $[ud]$ diquark mass: $m_{[ud]} = 578\ \mathrm{MeV}$
- Therefore each quark loses $75\ \mathrm{MeV}$ and its Fermi momentum is depleted: $m_{\text{final}} = \sqrt{m_q - \frac{BE}{2}}$

$$\text{Momentum ratio of quark in diquark to free quark :}$$

$$\frac{\mathrm{p_{final}}}{\mathrm{p_{initial}}} = \sqrt{\frac{\mathrm{m_f}}{\mathrm{m_i}}} \approx 0.89$$

Diquark structures in nuclei: X17 anomaly

- Possible effects of Hexadiquark Fock state in ^{4}He nuclear wavefunction →
- Based on "QCD hidden-color hexadiquark in the core of nuclei," *jrw, Brodsky, de Teramond, Goldhaber & Schmidt, 2021*
- NB: *HdQ predicts a bump in EMC effect for each α particle*

Quantum Chromodynamics Resolution of the ATOMKI Anomaly in ^{4}He Nuclear Transitions

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Recent observations of the angular correlation spectra in the decays $^4\text{He}^* \to {}^4\text{He} + e^+e^-$ and $^8\text{Be}^* \to {}^8\text{Be}+e^+e^-$ have been suggested as due to the creation and subsequent decay to an electron-positron pair of a new light particle with a mass of ~ 17 MeV. In this work, we present a calculation of the invariant mass $m_{e^+e^-}$ spectrum of the electromagnetic transition of an excited state of helium and estimate the differential and total width of the decay. We investigate the possibility that the source of the signal is an e^+e^- pair created by a new electromagnetic decay of ^{4}He caused by a proposed 12-quark hidden-color Fock state in the ^{4}He nuclear wavefunction, the "hexadiquark." We find that we can fit the shape of the signal with the QCD Fock state at excitation energy $E^* \simeq 17.9$ MeV and a Gaussian form factor for the electromagnetic decay. We address the physical issues with the fit parameters using properties of the hexadiquark state. In light of this work, we emphasize the need for independent experimental confirmation or refutation of the ATOMKI results as well as further experiments to detect the proposed new excitation of ^{4}He.

Introduction

Observations by the ATOMKI collaboration of anomalous angular correlations in electron-positron pairs produced in the nuclear decays $^4\text{He}^* \to {}^4\text{He} + e^+e^-$ [1, 2] and $^8\text{Be}^* \to {}^8\text{Be} + e^+e^-$ [3] have been attributed to the creation and subsequent decay of a new light particle to an e^+e^- pair of a new light particle with mass of ~ 17 MeV, dubbed the X17 or simply X. Recently, the same group reported observations of the lepton pair in the off-resonance region of $^7\text{Li}(\text{p}, \text{e}^+\text{e}^-)^8\text{Be}$ direct proton-capture reactions [4]. Our work in this article will focus on the ^{4}He experiment in which the observed invariant mass $m_{e^+e^-}$ of the lepton pair was found to be $m_X = 16.94 \pm 0.12(\text{stat.}) \pm 0.21$ (syst.) MeV. The Feynman diagram for this transition is shown in Fig. 1. The signal has generated a great deal of theoretical interest in both the particle and nuclear physics communities [5–25].

The light-front Fock state expansion of QCD has led to new perspectives for the nonperturbative eigenstructure of hadrons, including the quark-antiquark structure of mesons, the quark-diquark structure of baryons (such as the $|u[ud]\rangle$ composition of the proton) and the diquark-antidiquark structure of tetraquarks. In the case of nuclear physics, the color-singlet $|[ud][ud][ud][ud][ud][ud]\rangle$ "hexadiquark" Fock state has the same quantum numbers as the ^{4}He nucleus. The existence of the hexadiquark Fock state in the eigensolution of the ^{4}He nuclear eigenstate [27] can explain the anomalously large binding energy of the α particle. QCD also predicts orbital and radial excitations of the hexadiquark and thus novel excitations of ^{4}He beyond the standard excitations predicted by nucleonic degrees of freedom. The excitation energy of the hexadiquark can be below the energy required to produce hadronic decays such as $p + {}^3\text{H}$ and thus have evaded detection.

Fin

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